LakeSPI Assessment of 15 Auckland Lakes: 2021/2022

M D de Winton, S R Elcock, A T Taumoepeau. NIWA

June 2022

Technical Report 2022/21

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M D de Winton

S R Elcock

A T Taumoepeau

National Institute of Water and Atmospheric Research, NIWA

Auckland Council
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ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)

ISBN 978-1-99-110174-7 (Print)
ISBN 978-1-99-110175-4 (PDF)

This report has been reviewed by NIWA and RIMU scientists including Dr J Groom, RIMU
Approved for Auckland Council publication by: Name: Dr Jonathan Benge Position: Head of Research, Evaluation and Monitoring (RIMU)
Name: Sietse Bouma Position: Manager, Water Quality (RIMU)
Date: 30 June 2022

Recommended citation

de Winton, M. D., S. R. Elcock, A. T. Taumoepeau (2022). LakeSPI assessment of 15 Auckland lakes: 2021/2022. Prepared by the National Institute of Water and Atmospheric Research, NIWA for Auckland Council. Auckland Council technical report, TR2022/21

Cover image credit
NIWA diver completes survey records after a dive in Lake Kawaupaku, Auckland. Photograph by Aleki Taumoepeau, NIWA

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Executive summary

Auckland Council undertakes statutory environmental monitoring, including requirements under the National Policy Statement for Freshwater Management (NPS-FM). The LakeSPI (Submerged Plant Indicators) method was developed by NIWA to assess the ecological condition of lakes and more recently, two LakeSPI indices were adopted as ecosystem health attributes under the NPS-FM. These attributes assign lakes to bands A-D and sets a national bottom line as a minimum acceptable condition, with D band lakes falling below this bottom line. The NPS-FM directs that reassessments of these attribues is made every three years.

Auckland Council contracted NIWA to assess the ecological condition of 15 natural lakes within the Auckland region using LakeSPI. Surveys were completed between December 2021 and April 2022. Features of aquatic vegetation structure and composition were recorded and used to calculate three indices that are expressed as percentages of a lake's highest potential condition. A higher LakeSPI and Native Condition Index denotes better lake ecological condition and higher Invasive Impact Index denotes poorer lake condition. Lakes that do not have submerged vegetation (<10% plant cover) are termed 'non-vegetated', receive a default LakeSPI Index and Native Condition Index of 0%, and are considered to be highly impacted. Two lakes had been stocked with grass carp to eradicate aquatic weed and so were not considered suitable for a LakeSPI assessment.

The 13 assessed lakes had a wide range of current LakeSPI scores, ranging from a LakeSPI Index of 0% to 68%. Thirteen per cent of the Auckland lakes had a 'high' ecological condition, having substantial native vegetation character (Native Condition Index >50%) and the general absence of major impacts from invasive submerged weeds (Invasive Impact Index <50%). Thirteen per cent of lakes with a 'moderate' ecological condition reflected differing combinations of weed impact and native plant development. Thirty-nine per cent recorded a 'poor' condition (LakeSPI Index <20%), due to invasion by two of the worst submerged weeds in New Zealand, *Ceratophyllum demersum* or *Egeria densa*, giving an Invasive Impact Index ≥70% and Native Condition Index of ≤11%. Thirty-one per cent of lakes were 'non-vegetated'. This included two lakes that have previously had substantial submerged vegetation and two lakes that have been non-vegetated for >30 years.

All 13 lakes suitable for LakeSPI assessment had been previously assessed. Fifty-four per cent appeared to be in a stable condition, with changes in LakeSPI Index of ≤5% since the previous survey. Reductions in LakeSPI Indices of >5% suggested a declining lake condition for 31% of lakes. 15% of lakes showed improvement with a reduction in the Invasive Impact Index and an increase in the LakeSPI Index.

According to the NPS-FM, the attribute that uses the Native Condition Index placed 15% of assessed Auckland lakes into the B band and 15% into the C band. Sixty-nine per cent of lakes fell below the national bottom line into the D band for the Native Condition Index. The Invasive Impact Index placed 11% of nine assessed lakes into the B band and 78% into the C band. Just 11% (1 lake) fell below the national bottom line into the D band for Invasive Impact Index.

Risks to the ecological condition of Auckland lakes include water quality degradation, compounded by impacts from exotic fish, and invasion by invasive weeds in those lakes that retain native submerged vegetation. Lakes stocked with grass carp should be excluded from LakeSPI monitoring but vegetation status checked every five years, approximately. The remaining lakes should be resurveyed every three years, although there is scope to change this to annually if an intervention is undertaken or if a change in lake condition is suspected.

1. Introduction

Auckland Council undertakes statutory environmental monitoring to support policy development, including meeting requirements under the National Policy Statement for Freshwater Management (NPS-FM). The LakeSPI (Submerged Plant Indicators) survey method was developed by NIWA to assess the ecological condition of lakes (Clayton and Edwards 2006, de Winton et al. 2012). More recently, two indices derived from LakeSPI have been incorporated as new ecosystem health attributes under the NPS-FM[1] that have bands and national bottom lines. The LakeSPI method has now been applied to a large number of New Zealand lakes (>300), with a substantial proportion surveyed on more than one occasion. LakeSPI compliments traditional water quality monitoring, such as the Trophic Level Index method (Burns and Bryers, 2000), by providing additional ecological information. For example, LakeSPI focuses on the littoral edges of lakes where human interaction is the greatest and where impacts from inflowing water quality is often most apparent (Clayton and Edwards 2006).

In recent years Auckland Councilhas contracted NIWA to assess the condition of lakes within the Auckland region using LakeSPI and in 2021/2022 commisioned surveys for 15 lakes. A previous 2017 report (de Winton and Burton 2017) presented LakeSPI results for 33 surveyed waterbodiess in the Auckland Region, including all 15 lakes that were re-surveyed over 2021/2022. Further information on the history of submerged vegetation in lakes of the Auckland region, the nature of vegetation changes and the use of submerged plants as indicators can be found in Appendix A.

This report was prepared to update LakeSPI information for the region's priority 15 lakes since the 2017 report (de Winton and Burton 2017). LakeSPI scores for each lake are reported, accompanied by a brief description of vegetation character driving the scoring, and impacts or threats that may be facing these lakes are outlined, while changes in condition since 2017 are briefly described (see Results). Current LakeSPI scores for all 15 lakes are collated and ranked in order (see Current lake condition), together with an explanation of the main characteristics driving each score. Condition of the 15 Auckland lakes is briefly compared to LakeSPI results for lakes nationally (see National comparison) and lakes are scored according to the NPS-FM (see NPS-FM scoring). Finally, conclusions and resurvey recommendations are provided.

[1] exposure-draft-changes-to-npsfm-2020.pdf (environment.govt.nz), (https://consult.environment.govt.nz/freshwater/npsfm-and-nesf-exposure-draft/)

2. Study methods

2.1 LakeSPI

Curent LakeSPI results for 15 Auckland lakes were generated from surveys conducted specifically for this report (Table 1).

Table 1 – Lake grid reference (New Zealand Transverse Mercator Projection), size, and most recent LakeSPI survey date for 15 lakes assessed in the Auckland region specifically for this report.

Lake name	East NZTM	North NZTM	Lake Size (km²)	Most recent survey date
Kawaupaku	1730005	5915818	0.098	15/03/2022
Kereta	1714422	5949693	0.236	14/03/2022
Kuwakatai	1710982	5956779	0.278	17/03/2022
Okaihau	1728437	5925300	0.057	16/03/2022
Pehiakura Big	1743356	5883698	0.043	7/12/2021
Pehiakura Small	1743468	5883335	<0.01	7/12/2021
Pokorua	1744927	5882495	0.259	8/12/2021
Pupuke	1757588	5928039	1.038	21/04/2022
Rototoa	1710843	5958624	1.066	18/03/2022
Slipper	1746657	5995739	0.090	20/04/2022
Spectacle	1746747	5994660	0.438	20/04/2022
Te Kanae	1715290	5951255	0.056	16/03/2022
Tomarata	1748358	5993318	0.144	20/04/2022
Wainamu	1730872	5916363	0.150	15/03/2022
Whatihua	1748113	5873293	0.039	6/12/2021

Baseline LakeSPI sites at each surveyed lake have been selected that are representative of the lake vegetation. These sites are situated away from strong local influences that may alter the vegetation (e.g., inflows) and are GPS referenced (Appendix B).

At each site, scuba/snorkel divers scored 11 vegetation metrics (Figure 1) over a 2 m wide transect from shore to the deepest vegetation limit. Supplementary data of these metrics are available upon request.

Where divers were unable to make direct observations due to a dense algal bloom in Lake Pehiakura Big, surveyors used surface deployed hydroacoustics and grapnel drags, with searches by hand in shallow water on the lake margin. Hydroacoustics used a Lowrance™ depth sounder/GPS/chart plotter (models HDS 7 and 9, Navico Inc) and TotalScan Skimmer transducer with dual frequency of 200 and 455 kHz. The trace was reviewed for maximum weed bed height and major changes in plant cover. Grapnel sampling included targeted depth threshold criteria of the LakeSPI method (2.9m, 4.9m, 5.0m, 6.9m) and confirmed the deepest 10% cut-off for vegetation.

Recorded metrics for native vegetation assessment included:

- Native maximum depth – The maximum depth of native plants at >10% cover within any $2m^2$ surveyed area,
- Native ratio – the proportion of the vegetated transect occupied by native plants,
- Charophyte meadows – the maximum depth of the deepest-growing charophyte meadow that exceeds 75% cover within any $2m^2$ surveyed area.
- Native diversity – measures of diversity from the presence of representative species for key native plant community types,
- Native distribution – scored where any of three key native plant communities are found deeper than 5 m depth.

Metrics for invasive impact based on 10 invasive weed species included:

- Invasive ratio – the proportion of the vegetated transect occupied by invasive weeds,
- Invasive species impact – a score between 1 and 7 for the top ranked (most invasive) weed present,
- Invasive depth impact – measured from the maximum depth of invasive weeds at >10% cover within any $2m^2$ area,
- Nature of invasive cover – scores 5 categories of weed bed development,
- Invasive maximum height – records the maximum weed height.

An additional LakeSPI metric comprised:

- Vegetation maximum depth – the deeper of measures for native maximum depth or invasive depth impact.

A complete description of measured characteristics is given in the technical report and user manual at Lakespi (niwa.co.nz).

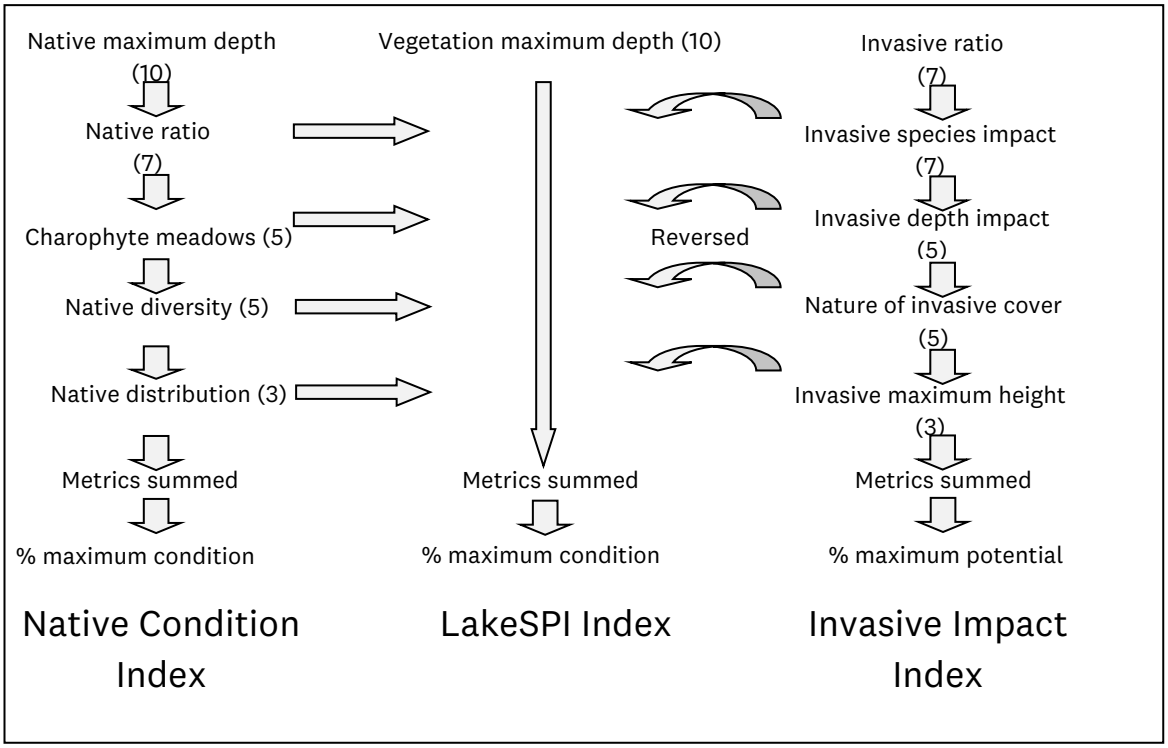


Figure 1 – Contribution of the eleven LakeSPI metrics to the three LakeSPI indices, with maximum metric score in parenthesis.

These key features of aquatic plant structure and composition are used to generate three LakeSPI indices (Figure 1) :

- 'Native Condition Index' – This captures the native character of vegetation in a lake based on diversity and quality of indigenous plant communities. A higher score means healthier, deeper, diverse submerged vegetation.
- 'Invasive Impact Index' – This captures the invasive character of vegetation in a lake based on the degree of impact by invasive weed species. A higher score means more impact from exotic species, which is often undesirable.
- 'LakeSPI Index' – This is a synthesis of components from both the Native Condition Index and Invasive Impact Index (inversed) of a lake and provides an overall indication of lake condition. The higher the score the better the condition.

Key assumptions of the LakeSPI method are that native plant species, high plant diversity and deeper vegetation extent are taken to represent healthier lakes or better lake condition, while invasive plants are ranked for undesirability based on their displacement potential and degree of measured ecological impact (Clayton and Edwards 2006).

Because lakes have differing physical characteristics that can influence the extent and type of submerged vegetation, each of the LakeSPI indices are expressed in this report as a percentage of a lake's maximum scoring potential. Scoring potential reflects the maximum depth of the lake to normalise the results from very different types of lakes. A lake scoring full points for all LakeSPI indicator criteria would result in a LakeSPI Index of 100%, a Native Condition Index of 100% and an Invasive Impact Index of 0%. Lakes that do not have expected submerged vegetation development (>10% plant cover) are termed 'non-vegetated' lakes and receive default Indices values of 0%.

The LakeSPI method is supported by a web-reporting service found at Lakespi (niwa.co.nz), where scores for lakes assessed to date can be searched and displayed. This secure and freely-accessible data repository allows agencies to compare lake scores with other lakes regionally and nationally as required.

2.2 LakeSPI status

For ease of reporting LakeSPI results, five lake condition categories are used to provide a description of a lake's status at the time of a survey. These categories provide a summary of the data, and allow for comparisons to be made between lakes along a scale of LakeSPI condition according to the LakeSPI Index value:

Score	= Category
>75%	= Excellent
>50-75%	= High
>20-50%	= Moderate
>0-20%	= Poor
0%	= Non-vegetated

2.3 LakeSPI changes

General guidelines (Figure 4) have been developed by NIWA to give a scale of probabilities for ecological change in lake condition with the extent of change in the LakeSPI indices over multiple surveys. These guidelines, based on expert judgment, have considered variation by different observers and the response of LakeSPI scores to major ecological events in lakes.

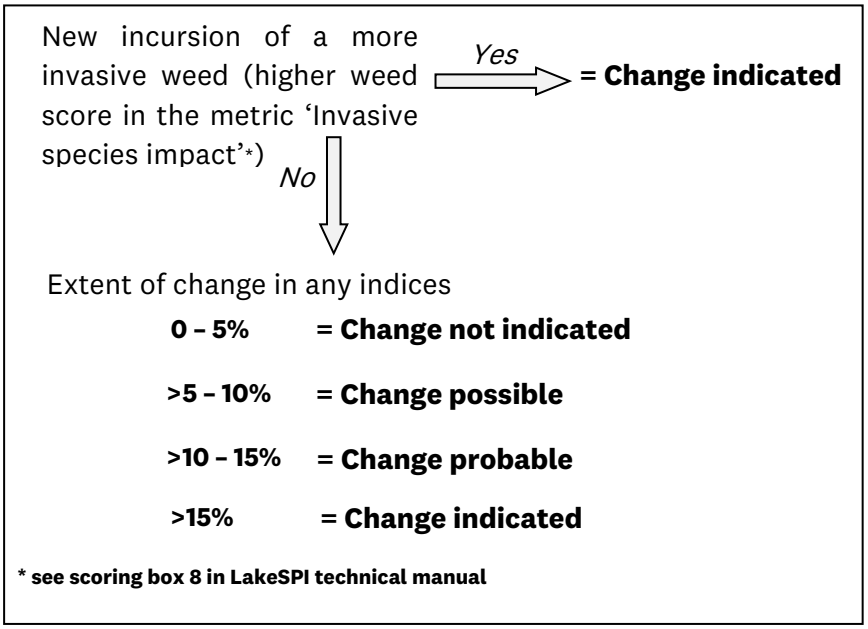


Figure 2 – Guidelines for assessing the significance of change in LakeSPI Indices over multiple surveys of a lake.

In addition, the likelihood of a statistically significant change in LakeSPI scores over time is based on analysis of the direction and magnitude of change in indices across the surveyed sites. A paired t-test (GraphPad InStat) was used to compare site results between surveys at the significance level $p < 0.05$.

2.4 National Policy Statement for Freshwater Management

The NPS-FM has included two LakeSPI indices as attributes in its National Objectives Framework (NOF) that require action plans (NPS-FM 2022[2], Appendix 2B, Tables 11 and 12). Attribute bands are related to Native Condition Index and Invasive Impact Index values as shown in Table 2. Any lake that falls below the national bottom line is considered degraded and may require councils to prepare a time-based action plan to achieve a target status. If the current state is below the national bottom line due to natural processes (e.g., naturally non-vegetated geothermal or peat lakes), a target attribute state below the national bottom line may be set. Currently, the Ministry for the Environment state that the Native Condition Index and Invasive Impact Index should be assessed every three years.

Invasive Impact Index for non-vegetated lakes is not included in the A band (Table 2), because lakes without submerged vegetation cannot be considered invaded or uninvaded.

Table 2 – National Objectives Framework attribute table for LakeSPI indices. Native Condition Index and Invasive Impact Index attribute bands from the NPS-FM (2020, Appendix 2B, Tables 11 and 12).

Attribute band	Native Condition Index	Invasive Impact Index
A	>75%	0*
B	>50 and ≤75%	>1 and ≤25%
C	≥20 and ≤50%	>25 and ≤90%
National bottom line	20%	90%
D	<20%	>90%

*Note Invasive Impact Index for non-vegetated lakes is not included in the A band.

[2] exposure-draft-changes-to-npsfm-2020.pdf (environment.govt.nz), (https://consult.environment.govt.nz/freshwater/npsfm-and-nesf-exposure-draft/)

3. Results

LakeSPI results for each lake have been presented in the form of a table identifying the LakeSPI Index, Native Condition Index, and Invasive Impact Index. Indices are presented as a percentage of each lake's maximum scoring potential and can be interpreted as follows:

HIGHER LakeSPI Index = Better lake condition.

HIGHER Native Condition Index = Better lake condition.

LOWER Invasive Impact Index = Better lake condition.

Descriptions of present day lake condition based on LakeSPI results are presented below by grouping lakes under five geographical groupings (Figure 3). The Te Arai Lakes include Tomarata, Spectacle and Slipper; South Kaipara group contains Lakes Rototoa, Kuwakatai, Te Kanae and Kereta; the Muriwai group are Lakes Okaihau, Wainamu and Kawaupaku; Auckland City refers to Lake Pupuke; the Awhitu Lakes are Pehiakura Big and Small, Pokorua and Whatihua. Within each geographical group, lakes are presented in order of decreasing LakeSPI scores.

Plant species lists based on the most recent surveys for each lake are presented in Appendix C.

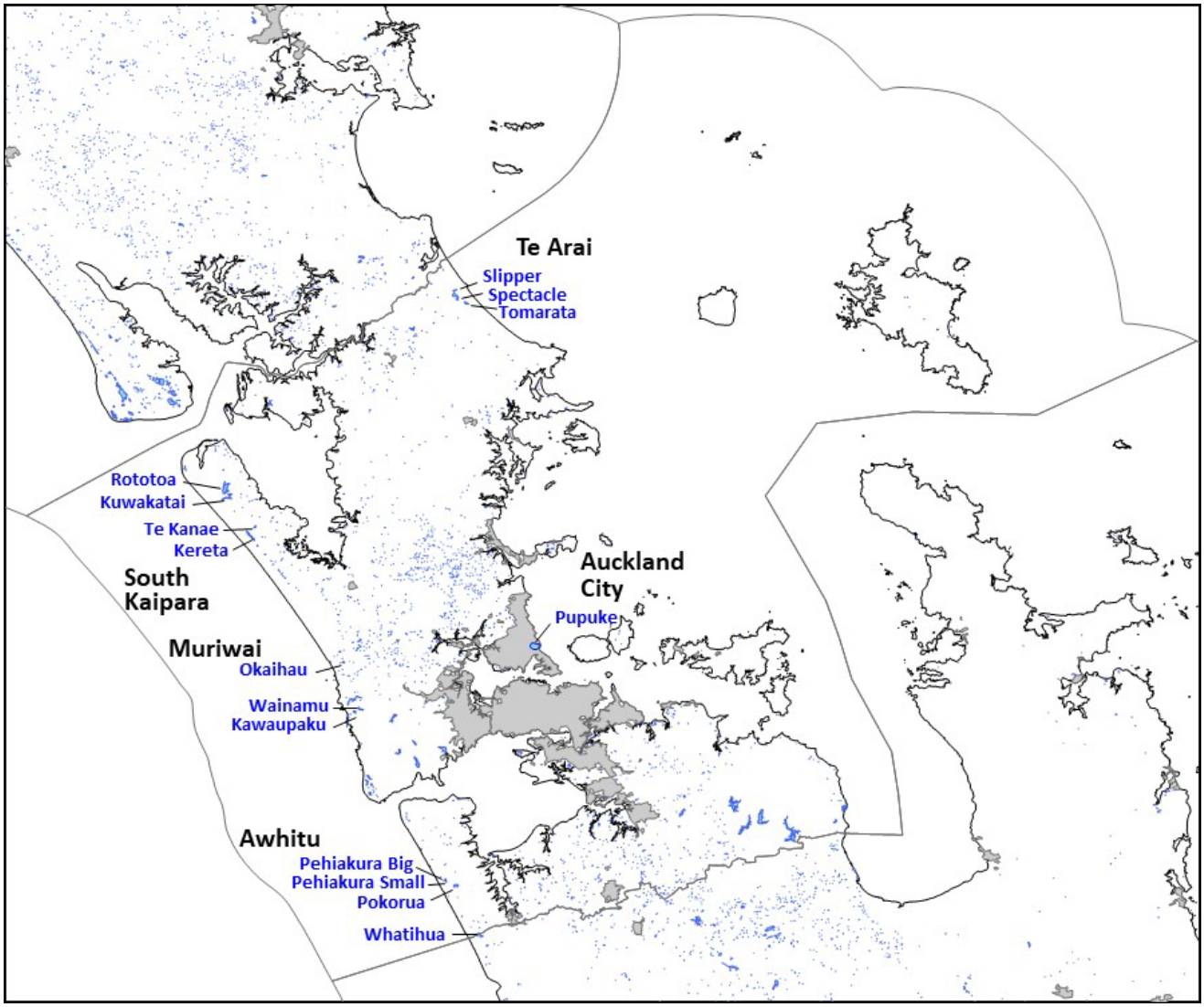


Figure 3 – Geographical grouping of Auckland region lakes.

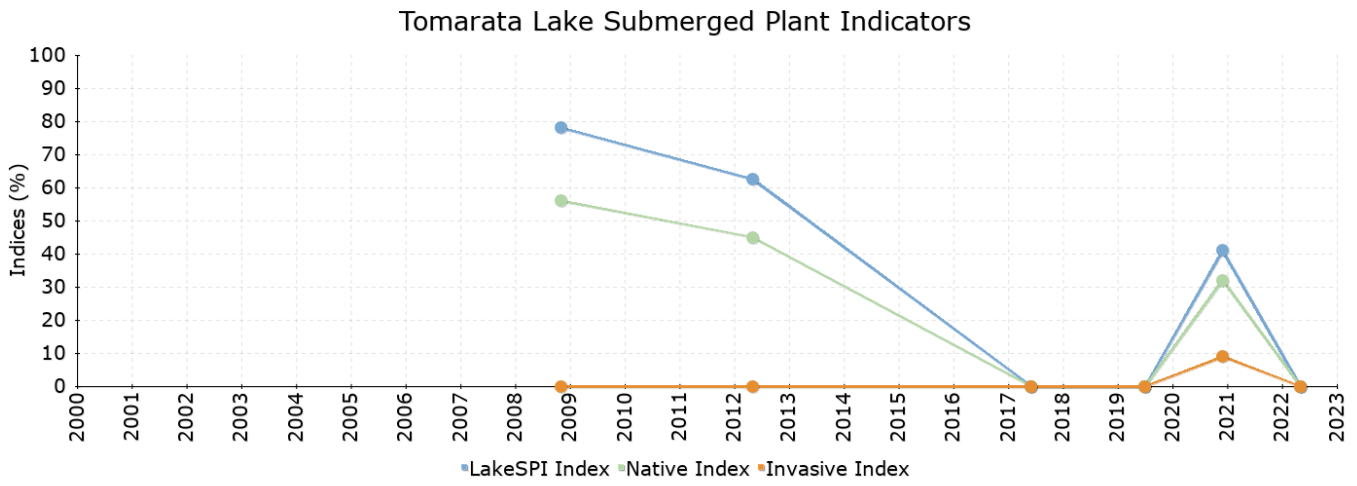
3.1 Te Arai Lakes

Lake Tomarata

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**Declining**
Lake Max Depth (m):	**6**
Lake type:	**Dune**

Results

In 2022, no significant submerged vegetation was present with vegetation covers much lower than 10%, therefore the lake scored a default LakeSPI value of 0% and falls into the 'non-vegetated' category (Figure 6). The Native Condition Index and Invasive Condition Index also scored a default of 0%.



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
April 2022	Non-vegetated	0.0%	0.0%	0.0%
November 2020	Moderate	41.0%	32.0%	8.9%
June 2019	Non-vegetated	0.0%	0.0%	0.0%
May 2017	Non-vegetated	0.0%	0.0%	0.0%
April 2012	High	62.5%	45.0%	0.0%
October 2008	Excellent	78.0%	56.0%	0.0%
August 1988	Excellent	76.9%	66.3%	11.1%

Figure 4 – LakeSPI results for Lake Tomarata. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Although individual plants of the native charophytes *Chara australis* and *Nitella pseudoflabellata* were present between 1.5 and 2.4 m depth at two sites (C and D, Appendix B) in 2022, covers did not exceed 1% (Figure 6A). The invasive bladderwort *Utricularia gibba* was also recorded at two sites (C and D, Appendix B), between 0 and 1.8 m depth at covers of much less than 10%. As in surveys of recent years (2022, 2020, 2019) evidence of fish disturbance of the lake bed was widespread (Figure 7B).

Earlier in 2020, Lake Tomarata scored a 'moderate' condition according to a LakeSPI Index of 41% (Table 3). At this time, a Native Condition Index of 32% reflected a patchy development of charophytes (three sites >75% cover to depths between 2.2 and 2.9) and an Invasive Impact Index of 9% (sparse *Utricularia gibba*). Observed fruiting by the charophytes was likely to have replenished the seed bank at this time.

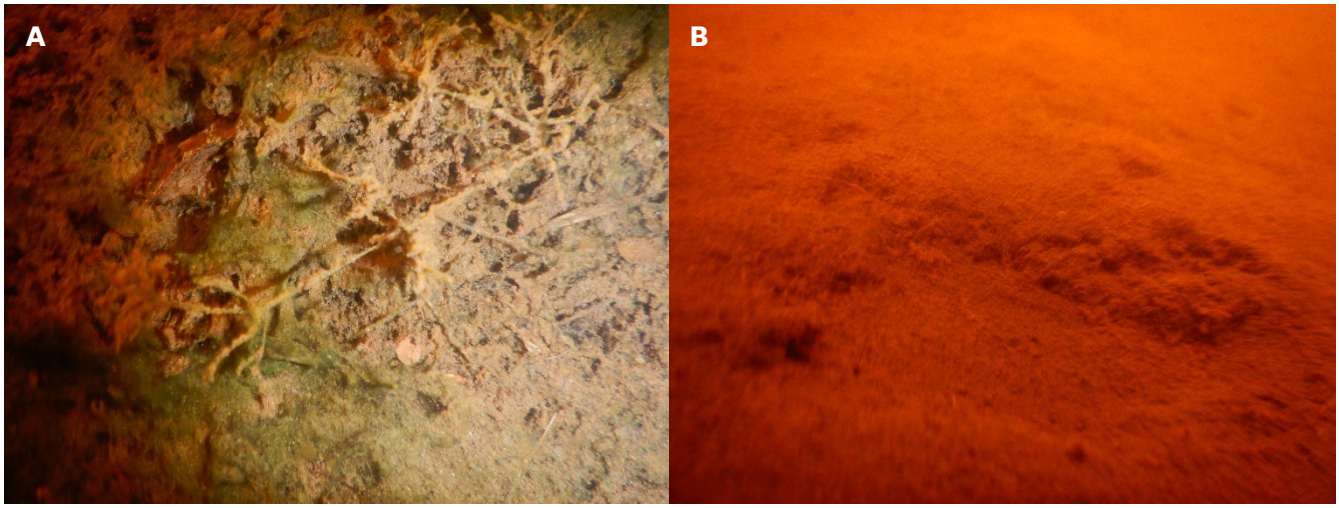


Figure 5 – Lake Tomarata had A) very sparse charophyte plants present and B) signs of fish disturbance of the sediment surface.

Previously in 2019, Lake Tomarata scored a default LakeSPI Index of 0% and was assigned to the LakeSPI category 'non-vegetated' (Table 3). Isolated germlings and young plants of native charophytes were encountered (<1% cover) to 2.2 m depth at three sites in 2019.

Discussion

Ecologically significant changes in the status of the predominantly native charophyte vegetation have occurred between the recent successive surveys of 2019 to 2022, although no statistically significant (paired T-test) change occurred due to the observed variability between sites.

Lake Tomarata was once dominated by native charophytes (pre-2012), but in 2022 only two species, *Chara australis* and *Nitella pseudoflabellata* was recorded at very low covers. Up to five charophyte species have been recorded from Lake Tomarata previously that have formed high cover 'meadows' (>75% cover). *Nitella leonhardii* and *Nitella* sp. aff. *cristata* were last recorded at LakeSPI survey sites in 2020 and *Chara fibrosa* was last recorded in 2008. *Utricularia gibba* has been present in the lake since 2008 but remains a minor component of the submerged vegetation.

Earlier observations (de Winton and Burton 2017) of retractions in the depth of charophyte meadows and low water clarity associated with subsequent loss of meadows, have suggested deteriorating water quality in Lake Tomarata over time. Other contributing factors to plant decline are thought to be disturbance by exotic fish including herbivourous rudd (*Scardinius erythrophthalmus*) and benthivourous tench (*Tinca tinca*) and koi carp (*Cyprinus carpio*) known at the lake (de Winton and Burton 2017). Possible impacts from recreational activities have also been reviewed (Wells 2016). The most recent (2019 to 2022) fluctuations in

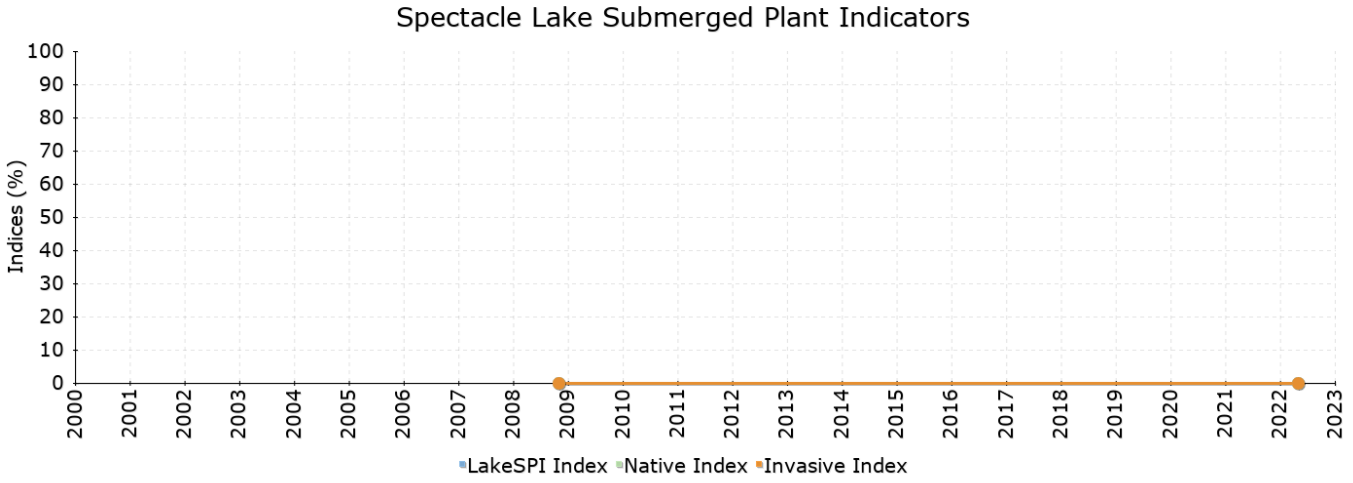
charophyte abundance are likely linked to cycles of seasonal charophyte germination and growth (spring to summer increases) and changing fish disturbance activity, with ongoing observations of plants on more stable substrates (e.g., emergent root mass) suggestive of physical disturbance by benthovorous fish. Similar communities of exotic fish have elsewhere been shown responsible in losses of charophyte germlings and established plants (de Winton et al. 2002, Dugdale et al. 2006).

Lake Spectacle

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**Stable**
Lake Max Depth (m):	**7 (4.5 detected)**
Lake type:	**Dune**

Results

In 2022, the lake continues to be categorised as a 'non-vegetated lake', with default LakeSPI Indices of 0% (Figure 6).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
April 2022	Non-vegetated	0.0%	0.0%	0.0%
October 2008	Non-vegetated	0.0%	0.0%	0.0%
August 1988	Non-vegetated	0.0%	0.0%	0.0%

Figure 6 – LakeSPI results for Lake Spectacle. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Discussion

Lake Spectacle has not recorded any submerged plant species during three surveys in the past 34 years. Ongoing poor water quality has been documented for this lake, having the worst water quality of seven lakes monitored in the Auckland region in 2015 (Hamill and Lockie 2015) and also in 1999 (Gibbs et al. 1999).

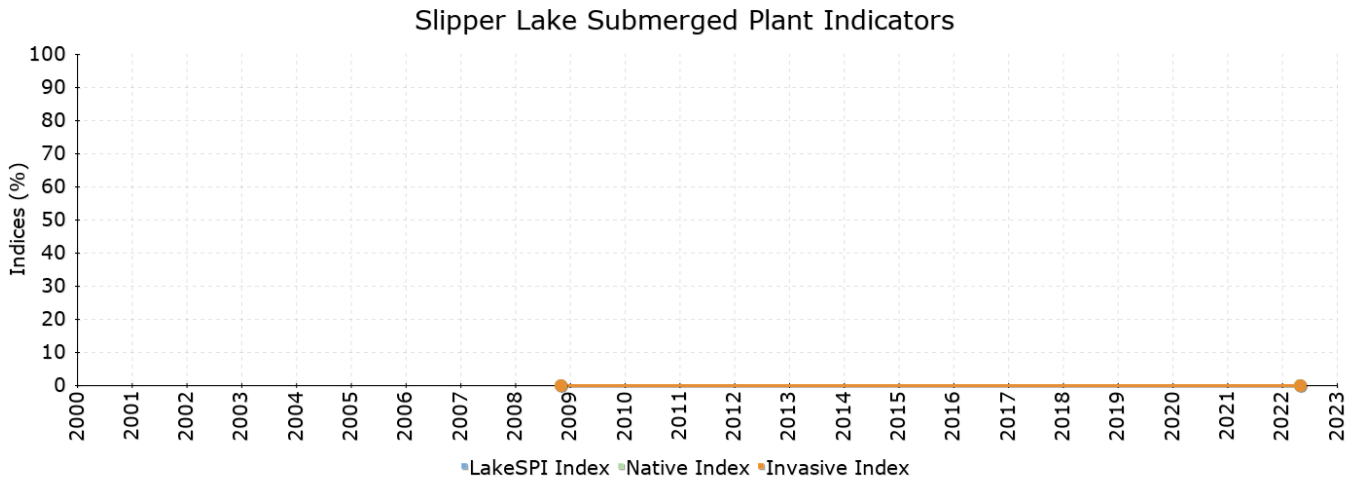
In addition to a low water clarity that would prevent estalishment of submerged vegetation over deeper parts of the lake bed, the shallow areas of Lake Spectacle are occupied by marginal vegetation. Additional stresses restricting submerged vegetation are the herbivorous rudd (*Scardinius erythrophthalmus*) that are known to have been present in this lake since 1979 (New Zealand Freshwater Fish Database).

Lake Slipper

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**Stable**
Lake Max Depth (m):	**5.3 (4.5 detected)**
Lake type:	**Dune**

Results

In 2022, Lake Slipper was a 'non-vegetated lake' with default LakeSPI Indices of 0% (Figure 7).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
April 2022	Non-vegetated	0.0%	0.0%	0.0%
October 2008	Non-vegetated	0.0%	0.0%	0.0%

Figure 7 – LakeSPI results for Lake Slipper. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Discussion

Lake Slipper has not recorded any submerged plant species during three surveys in the past 34 years. The lake is connected to Lake Spectacle via a wide drainage channel. Both lakes are likely to have similar water quality and exotic fish issues.

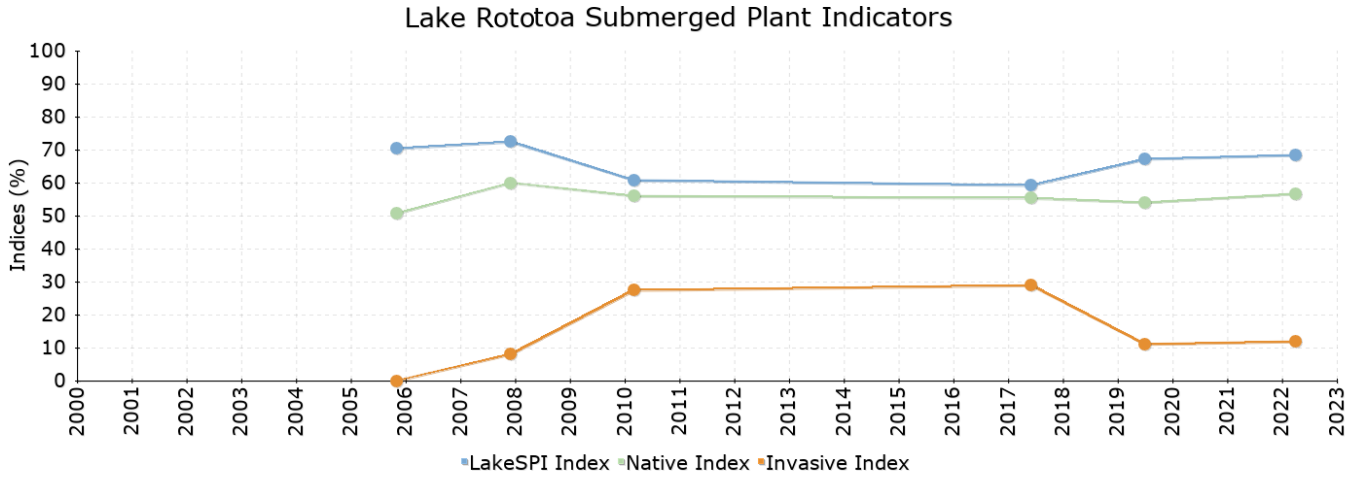
3.2 South Kaipara Lakes

Lake Rototoa

Latest assessment:	**2022**
Lake condition:	**High**
Stability:	**Stable**
Lake Max Depth (m):	**27.5**
Lake type:	**Dune**

Results

Lake Rototoa in 2022 had a 'high' ecological status with a LakeSPI Index of 68% (Figure 8). A Native Condition Index of 57% reflected the primarily native plant communities and relatively deep maximum extent of vegetation. The Invasive Impact Index of 12% showed the limited influence of invasive bladderwort (*Utricularia gibba*).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
March 2022	High	68.4%	56.7%	11.9%
June 2019	High	67.2%	54.0%	11.1%
May 2017	High	59.2%	55.3%	28.9%
February 2010	High	60.8%	56.0%	27.4%
November 2007	High	72.4%	60.0%	8.1%
October 2005	High	70.4%	50.7%	0.0%
February 1988	High	70.8%	51.3%	0.0%

Figure 8 – LakeSPI results for Lake Rototoa. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Lake Rototoa was dominated by charophytes, primarily *Chara australis* (Figure 9A) in deeper water to depths of up to 9 - 10.9 m, and native pondweeds (*Potamogeton ochreatus* and *P. cheesemanii)* in shallower water (Figure 9B) to depths between 4 and 7 m. Up to four additional charophyte species contributed to the vegetation, usually found in shallow water less than 5 m depth. Of note were large areas of reduced vegetation cover in the mid to deep zone (3-9 m depth) of Lake Rototoa that were associated with observations of sediment disturbance (Figure 9C) and reduced covers of charophytes. Beds of native emergent plants (*Machaerina articulata*, *M. arthrophylla* and *Eleocharis sphacelata*) were widespread around the lake margin. Although hornwort (*Ceratophyllum demersum*) is usually a high impact aquatic weed (Figure 9D), its distribution within Lake Rototoa has remained geospatially limited since 2007 and this weed was not recorded at any LakeSPI survey site in 2022. Hornwort distribution outside of these sites appeared to be associated with local enrichment, suggested by a very abundant blue-green algal association with the plants (Figure 9D).

LakeSPI results in 2022 did not differ significantly from 2020, which showed no significant differences since 2017, indicating the lake condition has been stable for some years recently.

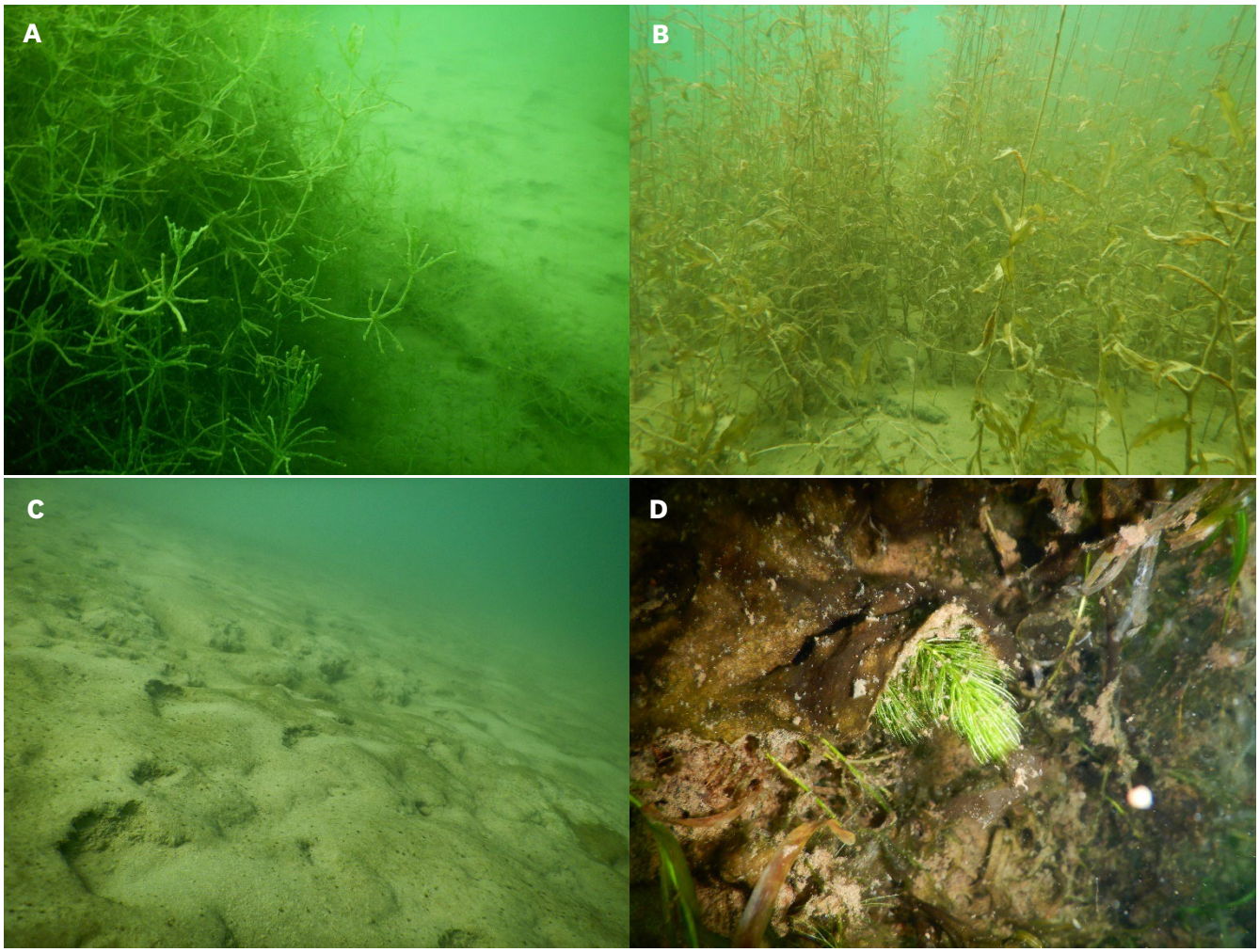


Figure 9 – The submerged vegetation of Lake Rototoa comprised A) deeper charophyte meadows of Chara australis and B) native pondweeds (Potamogeton ochreatus). Bare zones were common within the vegetated profile C) and showed signs of sediment disturbance by benthivorous fish. Hornwort (Ceratophyllum demersum) D) was not recorded at LakeSPI survey sites and remained at a limited distribution in the lake.

Discussion

LakeSPI indices have stabilised over the last 5 to 12 years after an earlier apparent reduction in ecological condition. However, the submerged vegetation has shown signs of degradation that are not fully captured by the LakeSPI assessment method, including denuded areas and shifts in plant species dominance or representation.

Of substantial concern is the high level of sediment disturbance usually associated with coarse fish browsing. In 2022, large areas of mid-depth vegetation were absent. However, a deeper bed of charophytes remained, recording a bottom depth limit that was largely unchanged since 2017. Vegetation and sediment disturbance were first observed near the maximum depth limit of vegetation in 2017 (de Winton and Burton 2017). Coarse fish, such as perch (*Perca fluviatilis*), goldfish (*Carassius auratus*), rudd (*Scardinius erythrophthalmus*) and tench (*Tinca tinca*) are recorded from the lake (New Zealand Freshwater Fish Database) and koi carp (*Cyprinus carpio*) were first noted in the lake in 2010 (de Winton 2010). These exotic fish represent disturbance pressure on the submerged vegetation (de Winton et al. 2002, Dugdale et al. 2006).

The development of cyanobacterial mats coating submerged plants were a noticeable feature of surveys since 2017.

In contrast, the expected impacts on the ecology of Lake Rototoa by invasive weed hornwort (*Ceratophyllum demersum*) have not yet eventuated. Hornwort was initially documented in Lake Rototoa from the north-western arm in March 2007 (de Winton 2010), but has remained absent or at low abundance (<10% cover) at all LakeSPI sites during all surveys. Invasive bladderwort (*Utricularia gibba*) has also remained limited to amongst the shallow reeds and rushes since 2007.

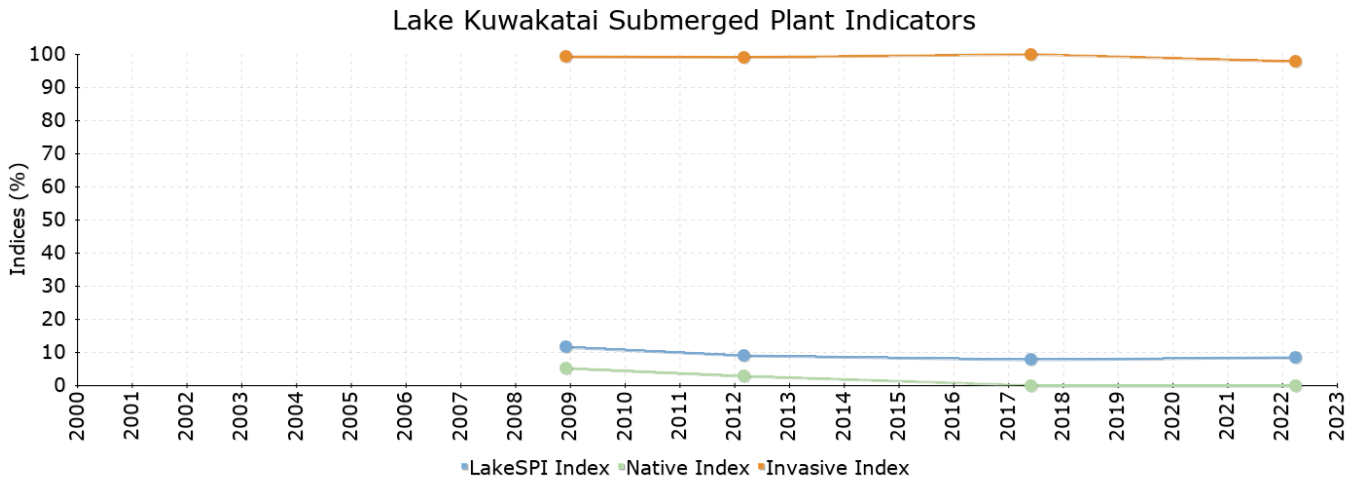
Lake Kuwakatai

Latest assessment:	**2022**
Lake condition:	**Poor**
Stability:	**Stable**
Lake Max Depth (m):	**15**
Lake type:	**Dune**

Results

In 2022, Lake Kuwakatai was categorised in 'poor' ecological condition with a LakeSPI Index of 9% and an Invasive Impact Index of 98% (Figure 10). The Native Condition Index was 0% (Figure 10).

The sole submerged plant species was hornwort (*Ceratophyllum demersum*), which comprised high cover (>75%) weed beds, up to 4 m tall (Figure 11A), to depths of between 6.1 to 8.6 m depth. Emergent plants, usually *Eleocharis sphacelata,* were widespread. Water clarity was poor for diver observations, with very low light conditions and etiolated hornwort (elongated stems between whorls of leaves) associated with blackened sediment at the lower plant boundary (Figure 11B).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
March 2022	Poor	8.5%	0.0%	97.8%
May 2017	Poor	7.7%	0.0%	100.0%
February 2012	Poor	9.0%	2.8%	99.1%
November 2008	Poor	11.5%	5.2%	99.3%
February 1988	Non-vegetated	0.0%	0.0%	0.0%

Figure 10 – LakeSPI results for Lake Kuwakatai. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

The 2022 results were not statistically significantly different from the survey results over 2008 to 2017 (Figure 10).

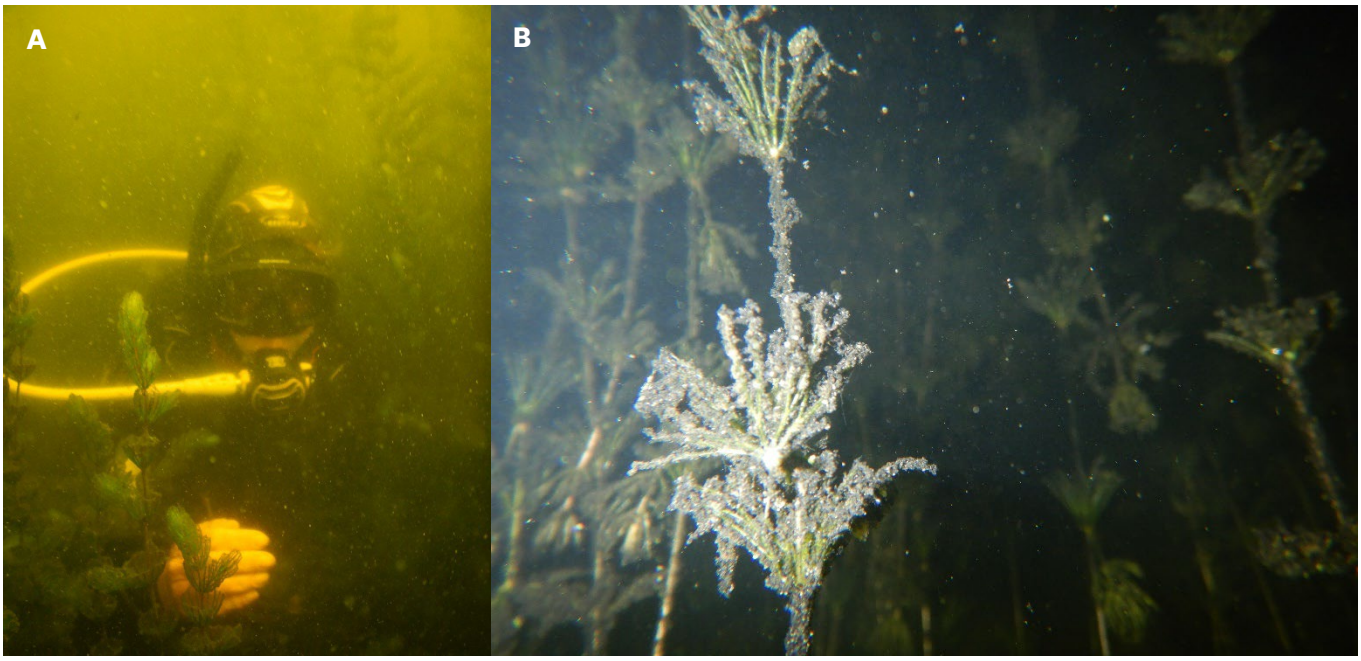


Figure 11 – Hornwort (Ceratophyllum demersum) at Lake Kuwakatai A) formed tall, dense beds above 5 to 6 m depth, with more open beds with etiolated stems below c.7 m depth.

Discussion

Lake Kuwakatai is in a stable, but highly impacted ecological condition due to invasions by alien weeds and exotic fish. Hornwort has been present since at least 1999. Previously only one native submerged plant, *Myriophyllum triphyllum*, has been encountered in the lake and this was uncommon. Large koi carp (*Cyprinus carpio*) were observed by divers in 2022 and 2017, and perch (*Perca fluviatilis*), goldfish (*Carassius auratus*), tench (*Tinca tinca*) and rudd (*Scardinius erythrophthalmus*) are also known from this lake (New Zealand Freshwater Fish Database).

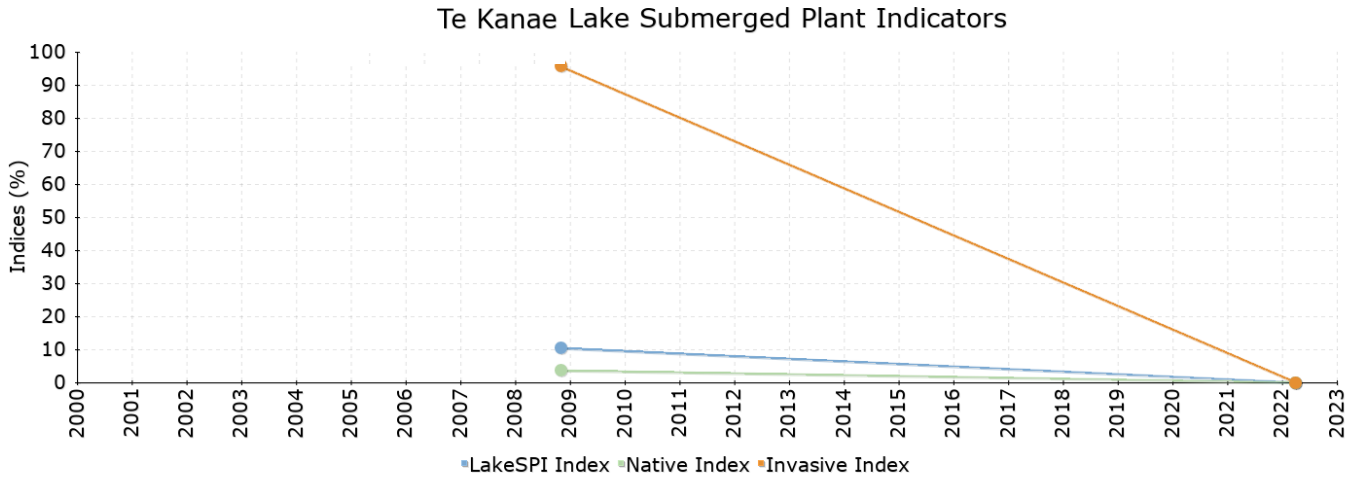
Hornwort has continued to dominate the lake and appears to be less susceptible to exotic fish disturbance due to this free-floating plant being non-reliant on root formation, its strong regeneration via fragmentation, and also a low palatability to herbivorous rudd (Lake et al. 2002). However, interactions between fish disturbance and poor water quality can lead to the loss of all vegetation, which is regarded as a greater ecological deterioration than weed dominance. Currently, hornwort is able to maintain a photosynthetic canopy within the surface upper waters on account of the very tall (4 m high) weed beds. If these weed beds are severely browsed or disturbed by fish, vegetation may experience extreme light limitation leading to its loss. The similarities of weed and fish species composition of Lake Kuwakatai to Lake Te Kanae (see below) might suggest a susceptibility for vegetation decline to a non-vegetated state.

Te Kanae Lake

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**Declining**
Lake Max Depth (m):	**18**
Lake type:	**Dune**

Results

In 2022, submerged vegetation did not exceed 10% cover at four of the five sites in Lake Te Kanae meaning it received default LakeSPI Indices of 0% (Figure 12) and was categorised as 'non-vegetated'. Hornwort (*Ceratophyllum demersum*) was recorded at low covers (≤5%) between 0.8 and 3.5 m depth at four sites. At an additional site at the central western shore (see Appendix B), hornwort formed a complete cover bed to 3.9 m depth (Figure 13A) with fragments extending to 4.5 m. No other submerged plant species were recorded. Emergent plants (e.g., *Eleocharis sphacelata)* were abundant at the lake margin to down to 1.4 m depth.



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
March 2022	Non-vegetated	0.0%	0.0%	0.0%
October 2008	Poor	10.4%	3.6%	95.6%

Figure 12 – LakeSPI results for Lake Te Kanae. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

LakeSPI results in 2022 represented a statistically significant reduction in the LakeSPI Index ($p<0.001$) since 2008, when a low LakeSPI index (10%) and very high Invasive Impact Index (96%) were recorded (Figure 12).

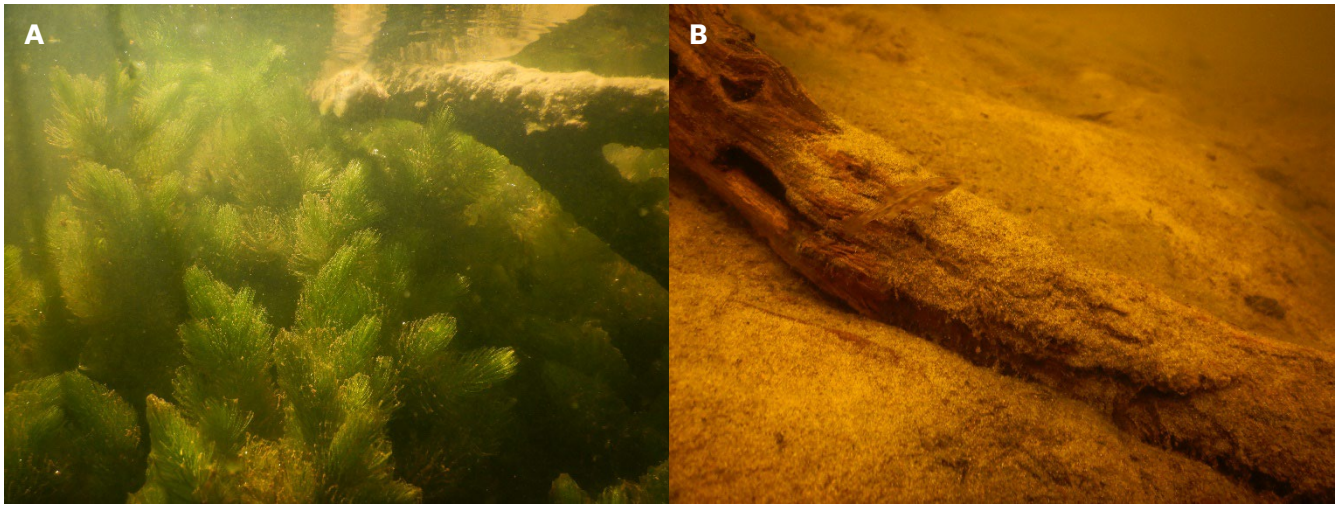


Figure 13 – Lake Te Kanae had A) very limited areas dominated by hornwort (Ceratophyllum demersum) and other parts of the lake B) were predominantly bare and sediment appeared to have been disturbed by fish.

Discussion

Koi (*Cyprinus carpio*), rudd (*Scardinius erythrophthalmus*) and tench (*Tinca tinca*) have all been liberated to Lake Te Kanae (Grant Leighton, landowner, pers comm. 2008) and a large koi was observed during the 2008 survey (de Winton and Burton 2017). Koi carp are frequently incompatible with significant submerged vegetation on account of direct plant disturbance (Crivelli 1983) and impacts on water quality (Rowe 2007).

Signs of sediment disturbance were observed in 2008 and in 2022 (Figure 13B), despite the substrate being sandy. It appears that fish disturbance may be responsible for the loss of submerged vegetation between 2008 and 2022, although interactions with water quality are also likely given the contrast between clear water conditions noted by divers in 2008 and restricted water clarity observed during the 2022 survey.

Lake Kereta

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**-**
Lake Max Depth (m):	**2.3 (reduced in 2022)**
Lake type:	**Dune**

Results

In 2022, Lake Kereta had an very low water level (c. 1 m maximum depth), the water was highly turbid with an algal bloom (Figure 15A-C) and no submerged plants were detected. The low water level had exposed muddy margins of the lakes where a number of grass carp (*Ctenopharyngodon idella*) frames were evident (Figure 15D), indicating recent fish mortality.

The non-vegetated status of the lake in both 2022 and 2012 is a direct result of grass carp stocking and therefore is not indicative of lake ecological condition. Earlier survey results (Figure 14) are discussed in de Winton and Burton (2017).

Lake Kereta Submerged Plant Indicators

Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
October 2008	Poor	7.6%	4.3%	95.6%
November 1999	Poor	14.7%	21.4%	92.6%
February 1988	Excellent	82.4%	66.7%	6.2%
January 1950	Excellent	100.0%	100.0%	0.0%

Figure 14 – LakeSPI results for Lake Kereta. LakeSPI Indices expressed as a % of lake maximum potential. Note no updated 2022 LakeSPI results due to grass carp status. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Discussion

Previously in 2008, almost the entire lake bed was covered by hornwort (*Ceratophyllum demersum*). Grass carp were stocked to the Lake Kereta over 2008-2009 to control this aquatic weed and resulted in complete vegetation loss. It appears that grass carp are still exerting sufficies browsing pressue in 2022 to prevent any vegetation recovery. Because the status of submerged vegetation has been artificially manipulated, LakeSPI Indices are not an appropriate measure for this lake.

Lake Kereta also contains other exotic fish, including rudd (*Scardinius erythrophthalmus*), perch (*Perca fluviatilis*), tench (*Tinca tinca*), goldfish (*Carassius auratus*) and koi carp (*Cyprinus carpio*), which will impact on water quality and lake ecological condition.

Lake Kereta today shows huge ecological differences compared to the earliest biophysical description in 1950. At that time, not only was a diverse submerged vegetation described, but an extensive bed of kākahi was noted (none located in the 2022 LakeSPI survey), the lake was much deeper (5 m) and fringed to the west by mobile sand dunes instead of the plantation pine forest seen today. Landscape changes in the catchment, altered limnological condition of a drying lake and introduction of non-native species have all impacted on lake ecological condition.

Figure 15 – Water level of Lake Kereta A) and B) was extremely low at the time of NIWA's survey, C) an algal bloom was noted and D) a number of grass carp frames were exposed at the margin of the lake.

3.3 Muriwai Lakes

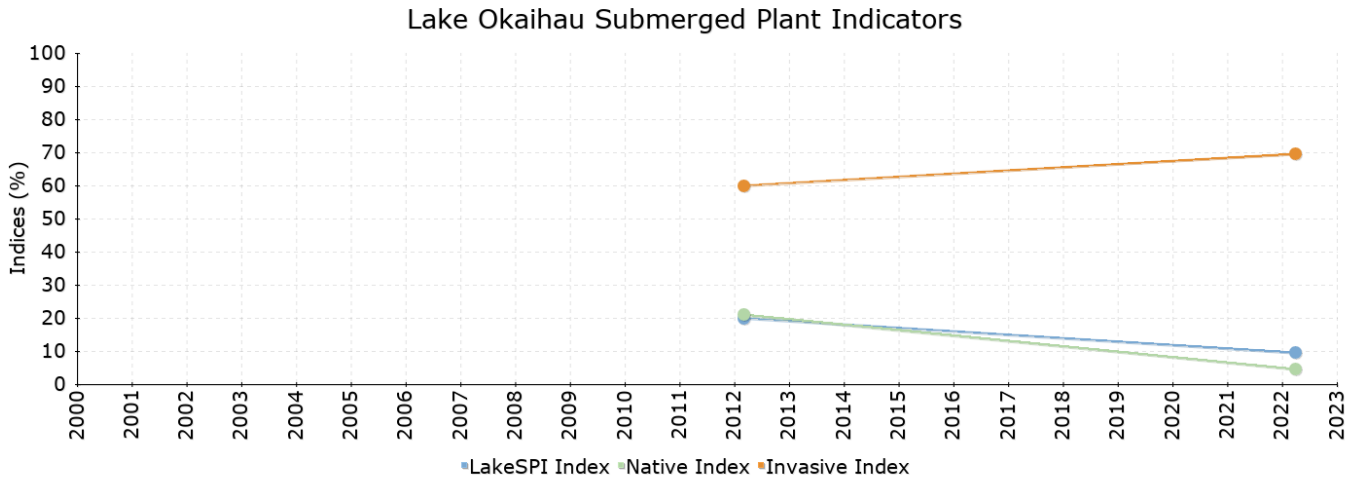
Lake Okaihau

Latest assessment:	**2022**
Lake condition:	**Poor**
Stability:	**Declining**
Lake Max Depth (m):	**12**
Lake type:	**Dune**

Results

In 2022, Lake Okaihau was categorised in a 'poor' ecological condition with a LakeSPI Index of 10% (Figure 16). The lake had a high Invasive Impact Index of 70% and very low Native Condition Index of 5%.

The submerged vegetation was dominated by hornwort (*Ceratophyllum demersum*), which was widespread to depths of 2.9 m, but only formed patches of high cover (>75%) at two out of the five surveyed sites (Figure 17A). Patches of waterlily (*Nymphaea* cultivars) were recorded at the lake margin at two sites that extended to between 1.8 to 2.8 m depth (Figure 17B). Native turf (*Glossostigma elatinoides*) was recorded in shallow water (0.2 m) at one site and a fragment of a charophyte species detected at an additional site.



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
March 2022	Poor	9.5%	4.5%	69.6%
February 2012	Poor	20.0%	20.9%	60.0%

Figure 16 – LakeSPI results for Lake Okaihau. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

No significant differences (t-test) were detected between 2022 and 2012 Indices as there was high variability between sites on both occasions.

Figure 17 – Dominant vegetation in Lake Okaihau in 2022 included A) hornwort (Ceratophyllum demersum), and b) waterlilies (Nymphaea cultivars).

Discussion

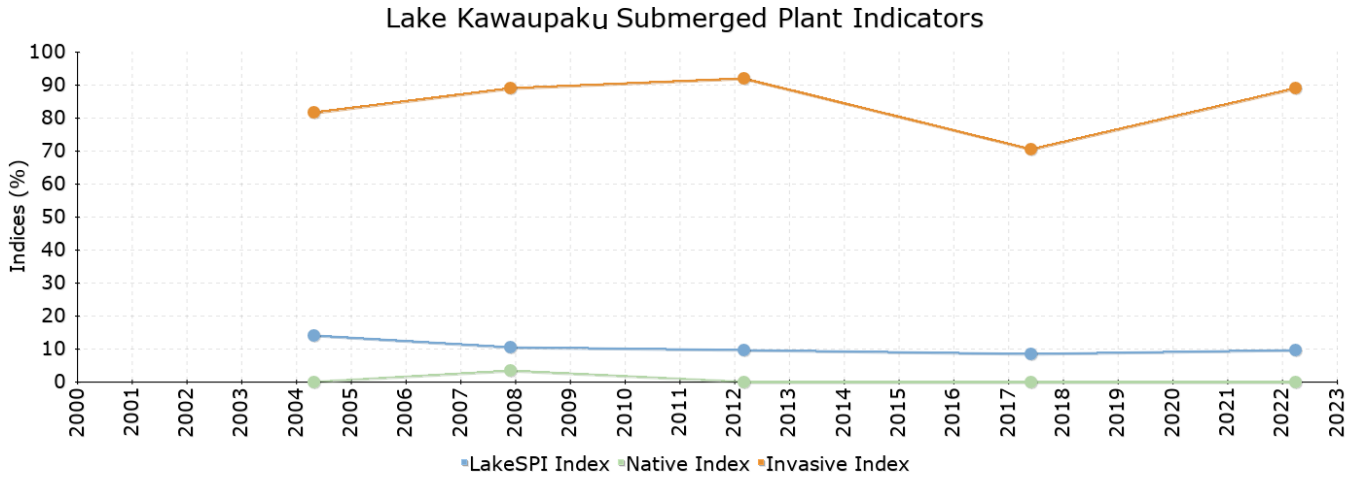
Lake Okaihau has been recorded in a 'poor' ecological condition since 2012 according to LakeSPI, and a similar state was described from a limited vegetation survey in 2005 (de Winton and Burton 2017). Turbid conditions, and the presence of rudd (*Scardinius erythrophthalmus*), recorded in 1974 (Cadwallader 1978) and confirmed during the 2012 LakeSPI survey, may account for the poor development of submerged vegetation. Apparent extirpation of egeria from the lake pre 2012 and milfoil between 2012 and 2022 also signals likely stress on submerged plants. Tench (*Tinca tinca*) and perch (*Perca fluviatilis*) are also recorded from Lake Okaihau (New Zealand Freshwater Fish Database).

Lake Kawaupaku

Latest assessment:	**2022**
Lake condition:	**Poor**
Stability:	**Stable**
Lake Max Depth (m):	**22**
Lake type:	**Dune**

Results

In 2022, Lake Kawaupaku remained in a 'poor' ecological condition with a LakeSPI score of 10%, an Invasive Impact Index of 89% and a Native Condition Index of 0% (Figure 18).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
March 2022	Poor	9.6%	0.0%	88.9%
May 2017	Poor	8.4%	0.0%	70.4%
February 2012	Poor	9.6%	0.0%	91.9%
November 2007	Poor	10.4%	3.3%	88.9%
April 2004	Poor	14.0%	0.0%	81.5%
January 1971	High	69.2%	48.7%	0.0%

Figure 18 – LakeSPI results for Lake Kawaupaku. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Egeria (*Egeria densa*) dominated all sites (Figure 19). Weed beds commonly exceeded 10% cover to an average of 3.7 m depth, with lower covers recorded to 4.9 m. Weed beds were commonly between 2 and 3

m in height. No native submerged plants were recorded, however native emergent (*Typha orientalis*, *Eleocharis sphacelata*, *Machaerina articulata*) were recorded at the lake margins.

The LakeSPI results from 2022 are similar to LakeSPI surveys recorded since a limited investigation in 2004 when egeria weed beds were first confirmed (Figure 18).

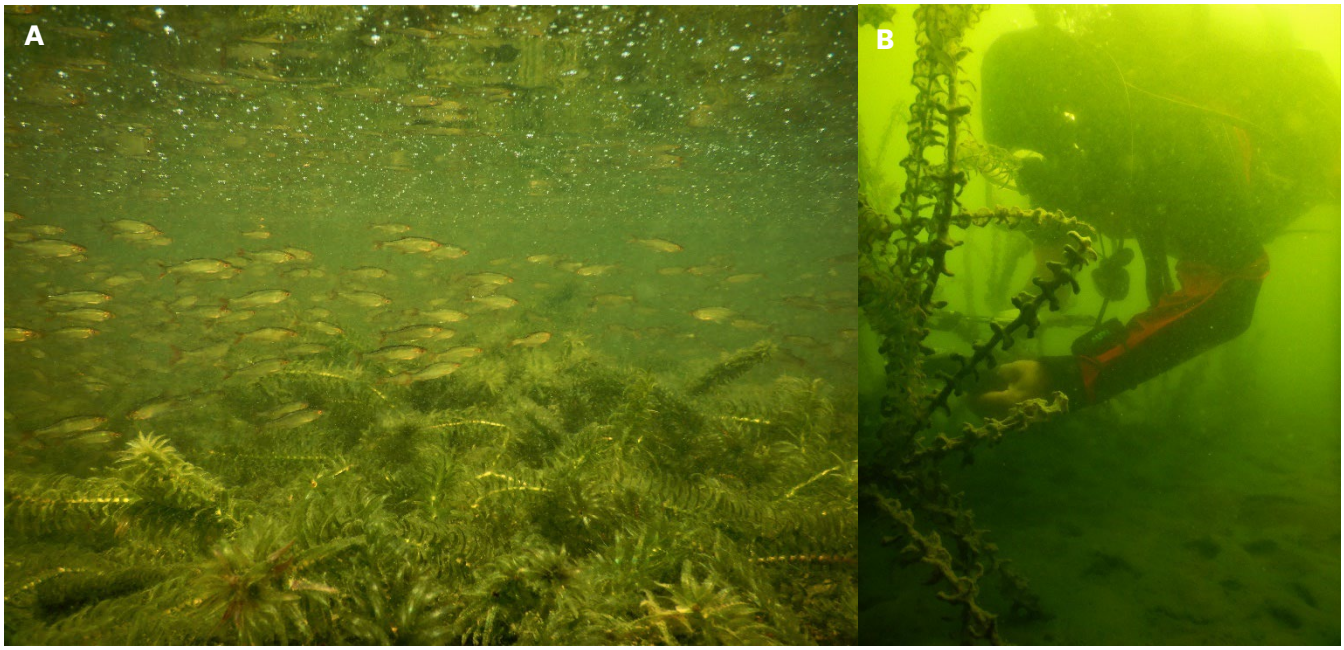


Figure 19 – Underwater at Lake Kawaupaku, A) numerous exotic rudd (Scardinius erythrophthalmus) and B) disturbance of the sediment surface by benthivorous fish in deeper water are likely to be impacting on the vegetation comprising beds of egeria (Egeria densa).

Discussion

Herbivorous rudd (*Scardinius erythrophthalmus*) and benthivorous tench (*Tinca tinca*) have been recorded in Lake Kawaupaku (New Zealand Freshwater Fish Database). It is of interest to note that the landowner has stated that the introduction of egeria coincided with the release of coarse fish (Champion and de Winton 2005). Also noted are observations of browsing and disturbance damage to egeria, particularly deeper plants, during the recent surveys. Large schools of juvenile rudd seen during the 2022 survey (Figure 12A) indicate that browsing by these herbivorous fish may be significant. In addition, surveys have often been undertaken when algal blooms have substantially reduced water clarity, including an algal bloom noted during the 2022 survey (Figure 19). So far, the poor water clarity and restrictions on egeria growth recovery from disturbance have not been sufficient to cause large retractions in depth extent or reduced cover (i.e., current stable lake status). However, the future risk of a wider vegetation decline is considered to be high.

Lake Wainamu

Latest assessment:	**2022**
Lake condition:	**Non-vegetated**
Stability:	**-**
Lake Max Depth (m):	**15**
Lake type:	**Dune**

Results

In 2022, Lake Wainamu remained 'non-vegetated' (submerged vegetation <10% cover) on account of the stocking of grass carp (*Ctenopharyngodon idella*) in 2009 to eradicate aquatic weeds. This 'non-vegetated' status has been recorded since late 2010 (de Winton and Burton 2017).

The status of the lake in both 2022 and 2012 was a direct result of grass carp stocking and therefore is not indicative of lake ecological condition. Earlier survey results (Figure 20) are discussed in de Winton and Burton (2017).

Lake Wainamu Submerged Plant Indicators

Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
November 2007	Poor	15.6%	16.0%	85.2%
October 2005	Moderate	23.8%	22.2%	73.5%

Figure 20 – LakeSPI results for Lake Wainamu. LakeSPI Indices expressed as a % of lake maximum potential. Note no updated 2022 LakeSPI results due to grass carp status. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Limited signs of submerged vegetation recovery were seen in 2022. Very sparse (<1% cover) charophyte plants (*Chara australis*, *Nitella* sp. aff. *cristata*) were recorded from the shallows (<2 m) at two survey sites (A and F, Appendix B). Invasive bladderwort (*Utricularia gibba*) was noted amongst shoreline emergent at two sites (B and E, Appendix B), but the majority of the lake bed was bare (Figure 21).

Figure 21 – Lake Wainamu had A) scattered clumps of invasive bladderwort (Utricularia gibba) amongst beds of emergents at the margin, but most of the lake bed B) was devoid of submerged plants.

Discussion

Because grass carp stocking artificially impacts on submerged vegetation, LakeSPI Indices are not an appropriate measure for Lake Wainamu. Stocked grass carp are likely to continue to restrict the development of submerged vegetation at Lake Wainamu, although this management action has apparently been successful in eradicating egeria from the system (the weed not seen since pre-2012). Grass carp are long lived (>30 years), can supress all submerged vegetation recovery at low fish numbers and can survive on terrestrial leaf litter and marginal emergent vegetation. Additional stressors for submerged vegetation at Lake Wainamu are a light environment that is restricted by on-going algal blooms. Lake Wainamu also records the presence of exotic fish with known impacts for submerged vegetation development, including perch (*Perca fluviatilis*), goldfish (*Carassius auratus*), tench (*Tinca tinca*), catfish (*Ameiurus nebulosus*) and herbivorous rudd (*Scardinius erythrophthalmus*).

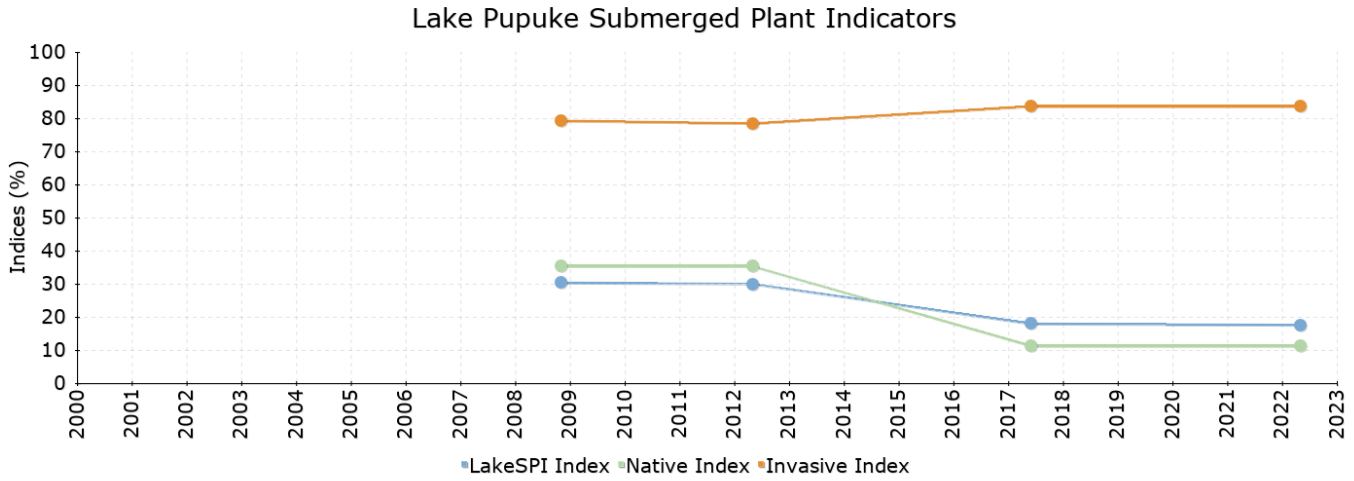
3.4 Auckland City Lakes

Lake Pupuke

Latest assessment:	**2022**
Lake condition:	**Poor**
Stability:	**Stable**
Lake Max Depth (m):	**58**
Lake type:	**Volcanic**

Results

In 2022, Lake Pupuke was categorised in 'poor' ecological condition with a LakeSPI Index of 18%, Native Condition Index of 11% and an Invasive Impact Index of 84% (Figure 22).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
April 2022	Poor	17.6%	11.3%	83.7%
May 2017	Poor	18.0%	11.3%	83.7%
April 2012	Moderate	30.0%	35.3%	78.5%
October 2008	Moderate	30.4%	35.3%	79.3%
June 1985	Moderate	25.6%	20.7%	76.3%

Figure 22 – LakeSPI results for Lake Pupuke. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

The lake's vegetation was dominated by two invasive weed species; eelgrass (*Vallisneria australis*) dominated in the shallower littoral zone to 3-6 m depth and egeria (*Egeria densa*) predominated in slightly

deeper water to a maximum of 7 to 8.6 m depth (Figure 23). Native submerged plants comprised a band of milfoil (*Myriophyllum triphyllum*) at the lake margin to 1.5 m depth and sparse charophytes (*Chara australis*) mostly found at the vegetation bottom limits (Figure 23) at two sites (B and E, Appendix B).

Survey results in 2022 scored almost identical indices values to 2017 (Figure 22), reflecting the similar vegetation composition at these times.

Figure 23 – Submerged vegetation at Lake Pupuke comprised A) eelgrass (Vallisneria australis) and egeria (Egeria densa), with B) egeria dominating in deeper water. Eelgrass root mats C) had commonly 'lifted off' the substrate. Remnants of the previous charophyte meadows D) could be seen at the deepest vegetation extent at two sites.

Discussion

Lake Pupuke is currently stable with a weed dominated submerged vegetation. Eelgrass has been known from Lake Pupuke since 1894 and egeria was introduced in the 1980s (Coffey and Clayton, 1987). More recent changes in vegetation composition have included reduced occurance of other aquatic weeds lagarosiphon (*Lagarosiphon major*), curled pondweed (*Potamogeton crispus*), and elodea (*Elodea canadensis*) and loss of deep charophyte meadows. Reduced vegetation depth limits by an average of 1.8 m after 2012 indicates water quality deterioration in the lake. Additional pressures on vegetation are likely from exotic coarse fish, given species composition recorded at the lake, which include perch (*Perca fluviatilis*) and goldfish (*Carassius auratus*), herbivorous rudd (*Scardinius erythrophthalmus*), and benthivorous tench (*Tinca tinca*) and koi carp (*Cyprinus carpio*).

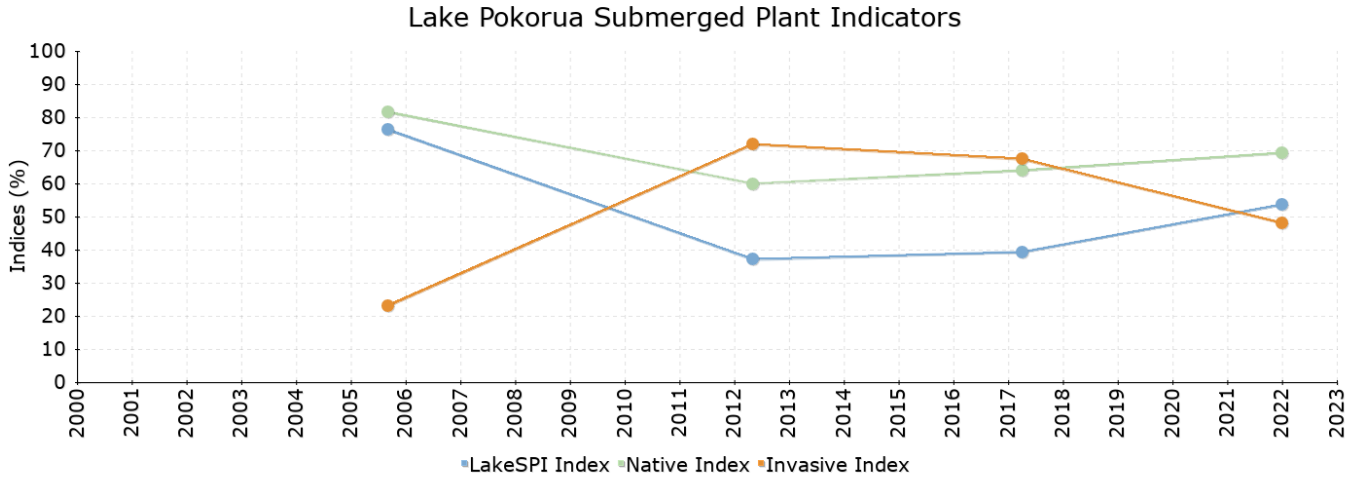
3.5 Awhitu Lakes

Lake Pokorua

Latest assessment:	**2021**
Lake condition:	**High**
Stability:	**Improving**
Lake Max Depth (m):	**4.5 (3.1 currently)**
Lake type:	**Dune**

Results

In 2021, Lake Pokorua was categorised in a 'high' ecological condition with a LakeSPI Index of 54%, a Native Condition Index of 69% and Invasive Impact Index of 48% (Figure 24).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
December 2021	High	53.7%	69.3%	48.1%
March 2017	Moderate	39.4%	64.0%	67.4%
April 2012	Moderate	37.1%	60.0%	71.9%
August 2005	Excellent	76.4%	81.7%	23.1%
April 1988	Moderate	37.1%	63.3%	75.9%
January 1950	Excellent	97.1%	93.3%	0.0%

Figure 24 – LakeSPI results for Lake Pokorua. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

This result reflected the predominantly native vegetation comprised of a mosaic of charophytes (*Chara australis*, *Nitella* sp. aff. *cristata*) and pondweed (*Potamogeton ochreatus*) that was recorded at >10% cover to an average of 2.0 m (Figure 25). Milfoil (*Myriophyllum triphyllum*) commonly occurred to 1.5 m

depth, with occasional plants of the charophyte *Nitella hyalina* and the salinity tolerant *Zannichellia palustris* also recorded in the shallows. No turf or emergent plants were recorded in the 2021 survey, probably due to the low lake level observed at this time.

The invasive weed elodea (*Elodea canadensis*) was common at all surveyed sites but never formed high cover beds (≤25% cover). Egeria (*Egeria densa*), which is considered a more invasive weed than elodea, was only encountered as scattered plants in 2021.

Compared to the previous survey in 2017, there had been a significant reduction in the Invasive Impact Index ($p<0.001$) and an increase in the LakeSPI Index ($p< 0.001$) in 2021.

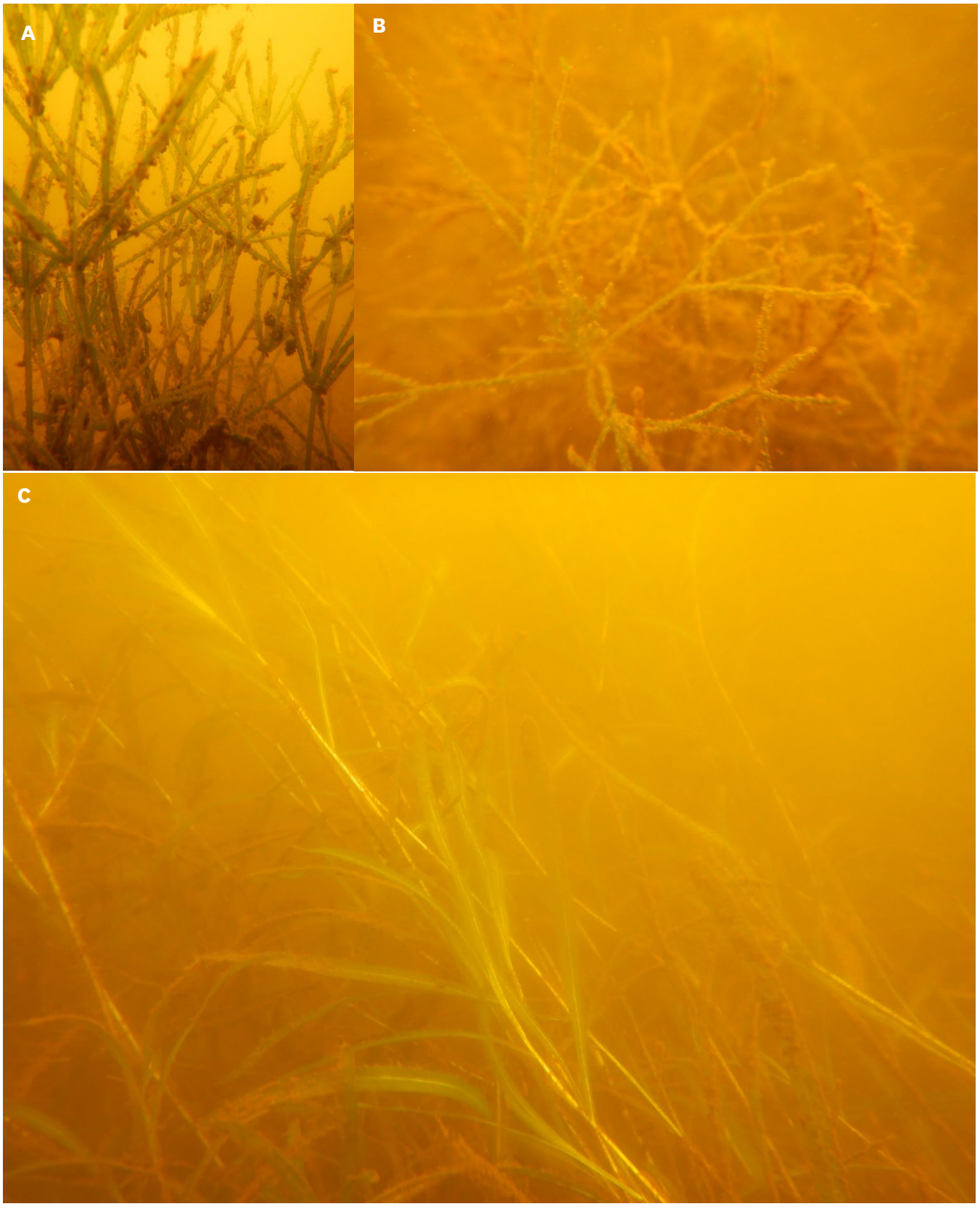


Figure 25 – Lake Pokorua vegetation comprised a mosaic of native charophytes A) Chara australis, B) Nitella sp. aff. cristata and C) the pondweed, Potamogeton ochreatus.

Discussion

Lake Pokorua has fluctuated in ecological condition according to LakeSPI over time. Similar values for LakeSPI Indices were obtained from the 2017, 2012 and 1988 surveys (Figure 24), which indicate a 'moderate' ecological condition. By contrast, a 'high' to 'excellent' lake ecological condition was derived from LakeSPI surveys in 2005 and 2021. These differences have reflected changes in the degree of invasion by egeria and, to a lesser extent, the depth of vegetation development (de Winton and Burton 2017).

Most of this variability has been driven by the impact of egeria. It could be that the improved LakeSPI conditions in 2005 and 2021 were driven by previous vegetation decline event in response to temporary increases in turbidity or algal blooms. Egeria and elodea, which are reliant on vegetative reproduction only, may recover more slowly than native plants that have the ability to recolonise from seed. Egeria appears to be particularly vulnerable to vegetation declines (Champion 2002, Schallenberg and Sorrell 2009). Alternatively, egeria may be responding to shifting nutrient conditions, as this weed is generally associated with higher lake trophic conditions.

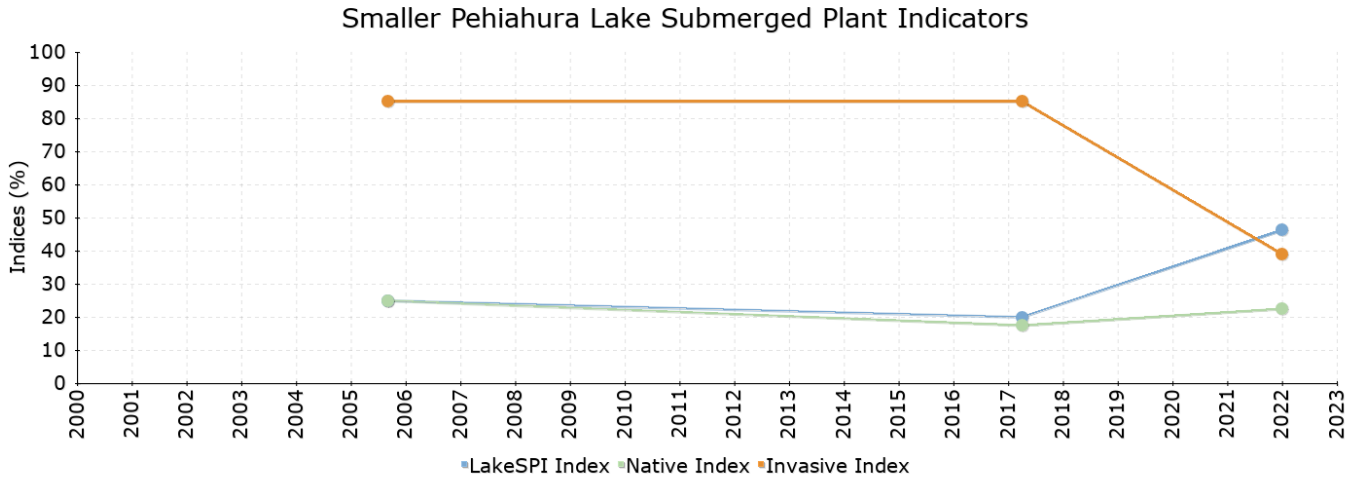
The differences in depth extent for significant vegetation of between 2.8 to 3.2 m in 2005, compared to 2.3 and 2.5 m in 2012, 2.0 to 2.3 m in 2017 and 1.9 to 2.2m in 2021 can also translate to a big difference in vegetated area in this shallow (c. 3 m deep), bowl-like lake. We note that the lake maximum depth appeared substantially deeper in 1950 at 6 m (Cunningham et al. 1953), compared to a maximum lake depth of 3.1 m detected in the 2021 survey.

Lake Pehiakura Small

Latest assessment:	**2021**
Lake condition:	**Moderate**
Stability:	**Improving**
Lake Max Depth (m):	**13**
Lake type:	**Dune**

Results

In 2021, Lake Pehiakura Small was categorised in a 'moderate' ecological condition with a LakeSPI Index of 46% (Figure 26). An Invasive Impact Index of 39% reflected the patchy presence of the aquatic weed egeria (*Egeria densa*), while a Native Condition Index of 23% was derived from a limited development by few indigenous plants.



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
December 2021	Moderate	46.3%	22.5%	38.9%
March 2017	Poor	20.0%	17.5%	85.2%
August 2005	Moderate	25.0%	25.0%	85.2%

Figure 26 – LakeSPI results for Lake Pehiakura (Small). LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Egeria formed open canopy (6-25% cover), patchy growths between 2.5 to 3.9 m depth, and usually 0.5 m in height (Figure 27). Unusually, egeria was absent from the upper 2.5 m of lake bed depth, even though conditions appeared suitable for anchorage and growth.

Native plants comprised scattered turfs of *Glossostigma elatinoides* in shallow water (Figure 27) and emergents including *Schoenoplectus tabernaemontani*. Elsewhere in the lake was observed sparse growths of the milfoil *Myriophyllum triphyllum* in the shallows (<0.5 m).

Overall in 2017, the lake had a 'poor' status according to a LakeSPI Index of 20% (Figure 26) with dense beds of egeria extending to almost 5 m depth.

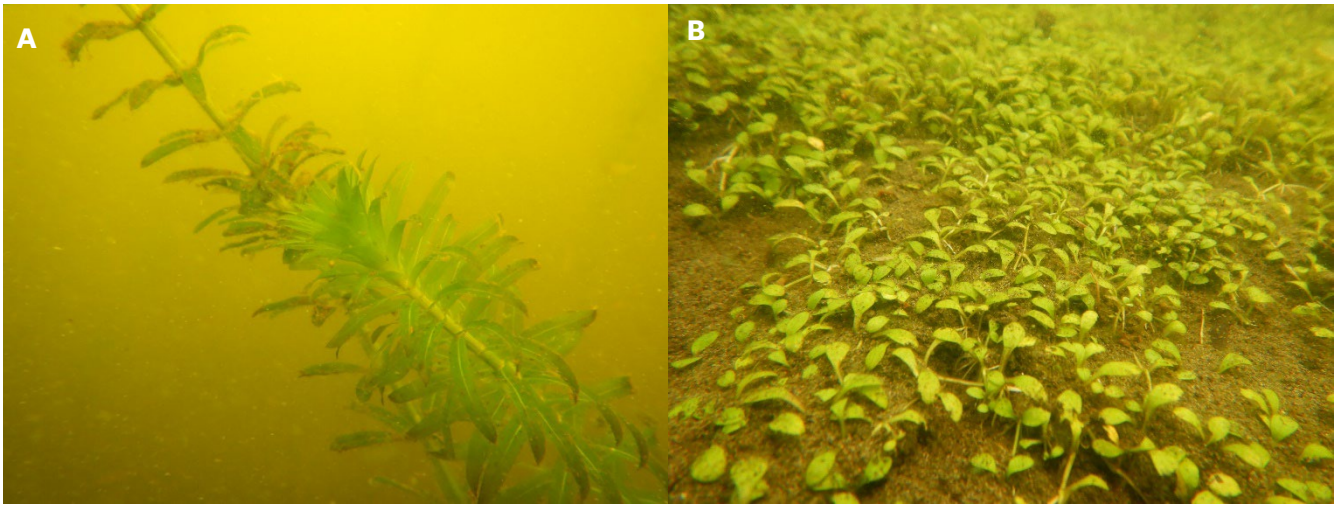


Figure 27 – Lake Pehiakura (Small) had A) scattered plants of egeria (Egeria densa) restricted to 2.5 to 4 m depth and B) native turf confined to very shallow water.

Discussion

Between 2017 and 2022, there has been a large decline in the egeria weed beds that previously dominated Lake Pehiakura Small. However, this reduction in invasive weed influence has not led to an expansion by native submerged plants. Therefore, the changes may not represent the improvement in ecological condition indicated by recent LakeSPI Indices, but instead may represent an instability in ecological state and a vulnerability to complete vegetation decline.

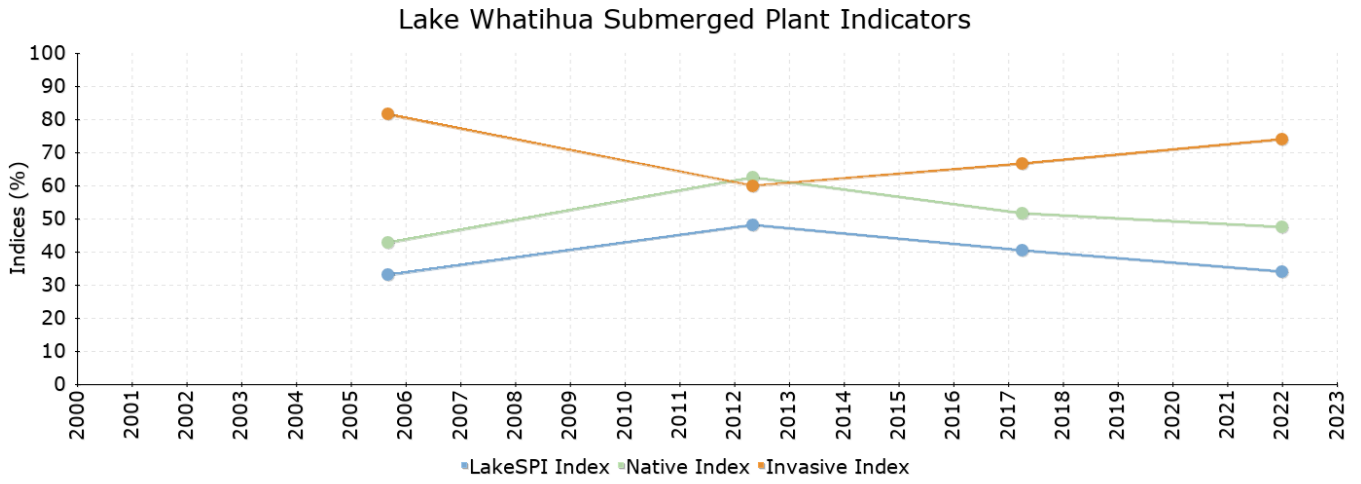
In 2021, algal blooms were noted in both Pehiakura Lakes. The response of submerged vegetation to light limitation at depth caused by poor water clarity is usually to retract to a shallower depth. However egeria was not recorded in the lake shallows <2.5 m. This suggests the current poor water clarity in the lake is not solely responsible for the recent weed bed reduction. The sighting of catfish (*Ameiurus nebulosus*) at the lake in 2005 raises the possibility of exotic fish impacts interacting with the apparent water quality issues (algal blooms) in structuring the submerged vegetation at this lake. It could be that patterns of grazing or browsing by exotic fish are responsible, where fish activity is focused within certain depth zones of higher water temperatures or dissolved oxygen levels. More information on the fish community composition of the Pehiakura Lakes would be useful.

Lake Whatihua

Latest assessment:	**2021**
Lake condition:	**Moderate**
Stability:	**Declining**
Lake Max Depth (m):	**11**
Lake type:	**Dune**

Results

In 2021, Lake Whatihua remained in a 'moderate' ecological condition according to a LakeSPI Index of 34%, with a Native Condition Index of 48% and an Invasive Impact Index of 74% (Figure 28). Vegetation was comprised mainly of Egeria (*Egeria densa*) and native pondweed (*Potamogeton ochreatus*).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
December 2021	Moderate	34.1%	47.5%	74.1%
March 2017	Moderate	40.5%	51.7%	66.7%
April 2012	Moderate	48.2%	62.5%	60.0%
August 2005	Moderate	33.0%	42.7%	81.5%

Figure 28 – LakeSPI results for Lake Whatihua. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Egeria (Figure 29A) contributed almost solely to the Invasive Impact Index of 74%. This weed dominated in the deeper littoral zone to an average of 5.1 m at >10% cover, with scattered plants recorded as deep as 6.1 m. Egeria was recorded as forming patches of >95% cover and growing up to 4 m tall. The weeds elodea (*Elodea canadensis*), and invasive bladderwort (*Utricularia gibba*), first recorded in 2017, continued to have a minor presence in the lake in 2021.

The Native Condition Index of 48% in 2021 was driven predominantly by the abundant, surface reaching beds of native pondweed (*Potamogeton ochreatus*), that was flowering and fruiting at the surface in a ring around the lake margin (Figure 2B and C). Native pondweed extended to an average of 4.8 m at>10% cover. Native turf plants, emergents and milfoils and mixed charophyte species (Figure 29D) continued to be recorded from the margins of the lake contributing to a diverse shallow water vegetation.

The 2021 results (Figure 28) did not differ significantly (t-test) from the 2017 survey results. However, some shifts were noted, with slightly deeper plant depths recorded in 2017 (5.6 m average cut-off for 10% cover), and lower egeria covers and heights (de Winton and Burton 2017).

Figure 29 – Vegetation at Lake Whatihua comprised A) deeper beds of egeria (Egeria densa), B) surface reaching beds of native pondweed (Potamogeton ochreatus) that was C) flowering and fruiting in shallow water and D) native charophytes limited to the lake margin at several sites.

Discussion

Lake Whatihua still represents the unusual example of an egeria invaded lake that has retained significant native vegetation diversity values. A total of 10 native submerged species were recorded from this lake in 2005 (Champion and de Winton 2005), 14 species in 2012, 13 in 2017 and 10 in 2021.

Egeria has been recorded in the lake since at least 1987. Egeria is thought to be most competitive under eutrophic conditions, but the fact that it is co-existing with native species suggests trophic level conditions

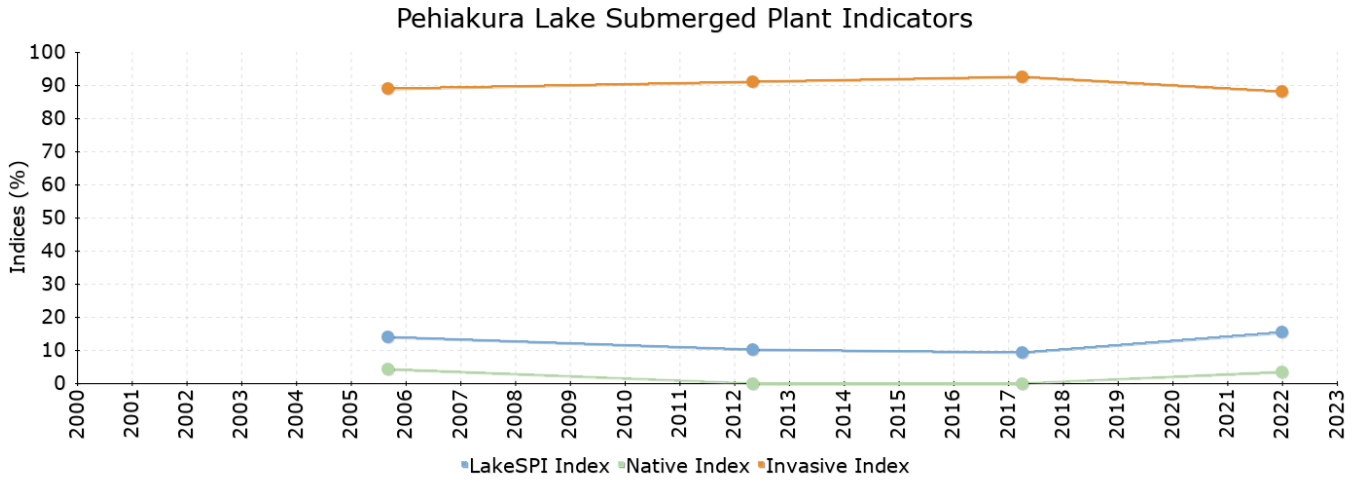
are not yet been optimal for this weed. Conversely, the ongoing reductions in submerged vegetation depths over recent successive surveys, particularly the average reduction of 2.6 m depth between 2012 and 2017 (de Winton and Burton 2017), suggests water quality has been impacted by nutrient enrichment with flow-on effects on water clarity and light penetration. For this reason, the lake is considered to be declining in ecological condition.

Lake Pehiakura Big

Latest assessment:	**2021**
Lake condition:	**Poor**
Stability:	**Stable**
Lake Max Depth (m):	**10.7**
Lake type:	**Dune**

Results

In 2021, Lake Pehiakura Big remained in a 'poor' ecological condition with a LakeSPI Index of 15% (Figure 30). A high Invasive Impact Index of 88% was owing to the dominance of the weed egeria (*Egeria densa*) and negligible presence of native submerged plants (Native Condition Index of 4%).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
December 2021	Poor	15.3%	3.5%	88.1%
March 2017	Poor	9.3%	0.0%	92.6%
April 2012	Poor	10.2%	0.0%	91.1%
August 2005	Poor	14.0%	4.3%	88.9%

Figure 30 – LakeSPI results for Lake Pehiakura Big. LakeSPI Indices expressed as a % of lake maximum potential. See de Winton and Burton (2017) for narrative on LakeSPI results prior to 2017.

Egeria weed beds were recorded to an average depth of 5.5 m depth at >10% cover (based on hydroacoustic and grapnel sampling, see methods) and formed complete covers to 3 m in height over much of this depth range (Figure 31A). Grapnel samples from deeper water indicated likely light stress with

some defoliation and 'mushy' stems of plant material (Figure 31B). The only other submerged plants detected were two species of native charophyte in shallow water <1 m at the margin of one site (Figure 31C and D). This is the first time that native submerged species have been detected by LakeSPI surveys since 2005. A narrow, but almost continuous band of emergent plant species exists around the lake margin.

Although LakeSPI indices values in 2021 were similar to previous LakeSPI surveys since 2005 (Figure 30), the Invasive Impact Index in 2021 was significantly lower ($p<0.01$) than 2017 on account of a shorter weed bed (up to 3 m tall and not surface-reaching in 2021). The LakeSPI Index was also significantly higher ($p<0.05$) on account of slightly deeper vegetation extent in 2021 and the detection of native submerged plants. The range in depth of main weed bed extent in 2021 of 5.1-5.9 compares to 4.2-4.5 m in 2017, 3.5-4.3 m in 2012 and 5.4 m in 2005.

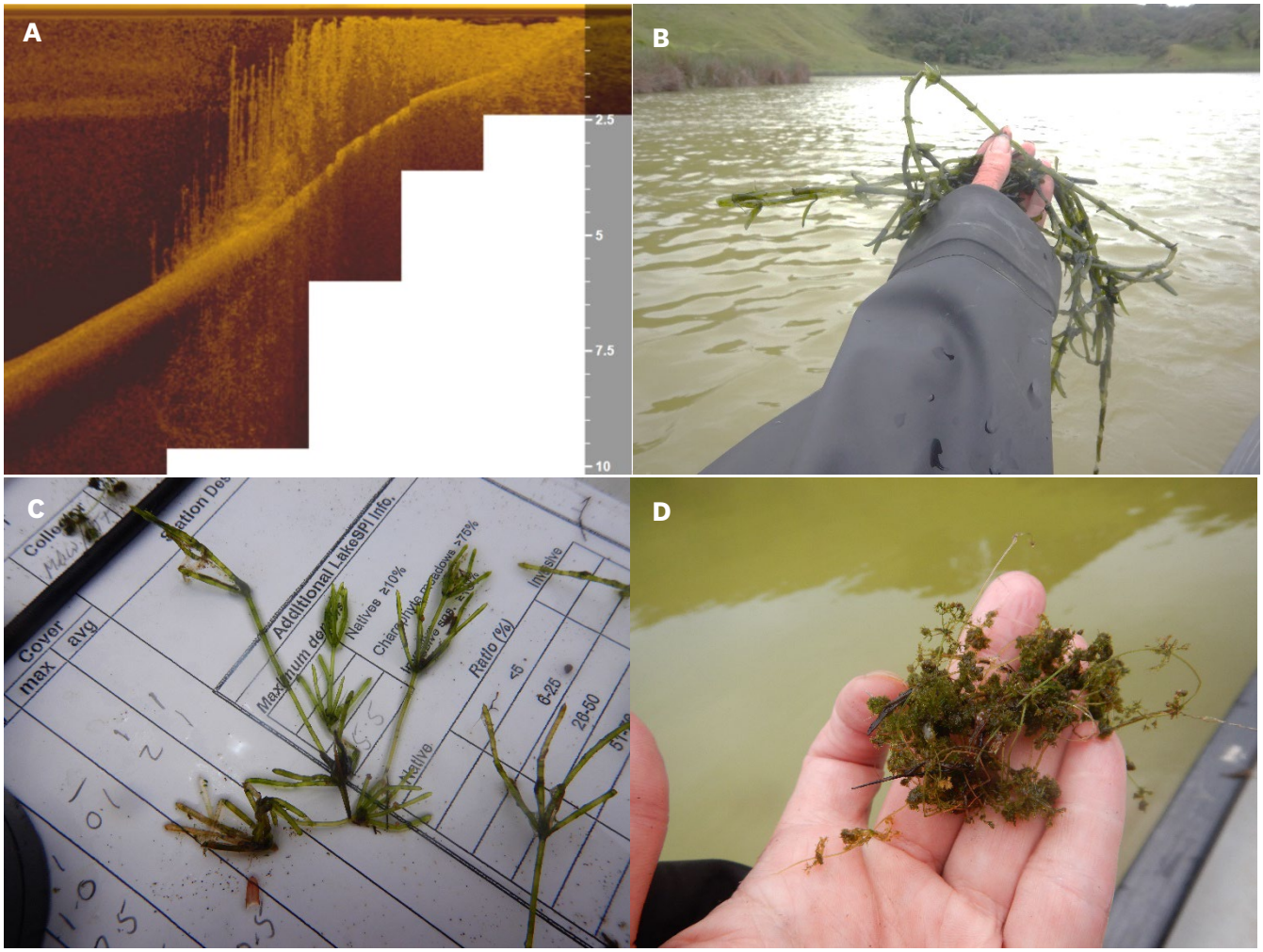


Figure 31 – Vegetation at Lake Pehiakura Big shown by A) a hydroacoustic trace of weed beds dominated by egeria (Egeria densa) to 5-6 m depth, but B) deeper plants were partially rotted and generally unhealthy, probably due to light stress under the prevalent algal bloom conditions. Native charophytes C) Chara australis and D) Nitella hyalina were located at one site in the shallows.

Discussion

Lake Pehiakura Big remains in a stable but highly impacted state, due largely to the dominance of egeria, and continues to indicate a ‘poor’ ecological condition. Low water clarity due to recurrent algal blooms at the lake are likely to stress submerged plants due to a restricting light climate for growth and survival. However, egeria is able to escape some light stress by forming a very tall canopy of photosynthetic tissue close to the water surface. Small fluctuations in depth extent may result from local death and bed retraction at the bottom limit for plants, as possibly indicated in 2021, but to date the egeria beds have appeared to be stable. We note that egeria dominated vegetation is particularly susceptible to vegetation declines and a shift to an algal dominated state (Champion 2002, Schallenberg and Sorrell 2009).

4. Discussion

4.1 Current lake condition

The 15 lakes of the Auckland region have a wide range of current LakeSPI scores ranging from those that have no submerged vegetation and a LakeSPI Index of 0%, up to a maximum of 68% (Table 3, Figure 32).

For the purposes of ranking and discussing these results, the 15 Auckland lakes have been categorised into lake condition categories according to their current LakeSPI Index, as high, moderate, poor and non-vegetated (Table 3, Figure 32). No lakes in the Auckland region fell into the excellent category for LakeSPI results.

Additionally, the lakes have been further divided based on the apparent impacting factor influencing the score. Impacting factors include 'weed' invasion (Invasive Impact Index ≥60%), vegetation development limited by 'water quality', and likely impacts from coarse fish disturbance. Note that while a default Invasive Impact Index value of 0% has been assigned to non-vegetated lakes, this group of lakes cannot be 'invaded' as vegetation development is negligable. Also, where grass carp have been utilised as a weed control measure, this makes a LakeSPI assessment inappropriate (Table 3).

Table 3 – Summary of current LakeSPI results for assessed lakes with overall condition category and an indication of the main impact factor on scores.

Lake	LakeSPI Index (%)	Native Condition Index (%)	Invasive Impact Index (%)	Overall condition	Impact factor
Rototoa	68	57	12	High	Water quality/coarse fish
Pokorua	54	69	48	High	Water quality
Pehiakura Small	46	23	39	Moderate	Water quality/coarse fish
Whatihua	34	48	74	Moderate	Weed/water quality
Pupuke	18	11	84	Poor	Weed/water quality
Pehiakura Big	15	4	88	Poor	Weed/water quality
Kawaupaku	10	0	89	Poor	Weed/water quality/coarse fish
Okaihau	10	5	70	Poor	Water quality/weed/coarse fish
Kuwakatai	9	0	98	Poor	Weed/ water quality
Tomarata	0	0	0	Non-vegetated	Water quality/coarse fish
Te Kanae	0	0	0	Non-vegetated	Water quality/coarse fish
Slipper	0	0	0	Non-vegetated	Water quality
Spectacle	0	0	0	Non-vegetated	Water quality
Wainamu	-	-	-	Non-vegetated	Grass carp
Kereta	-	-	-	Non-vegetated	Grass carp

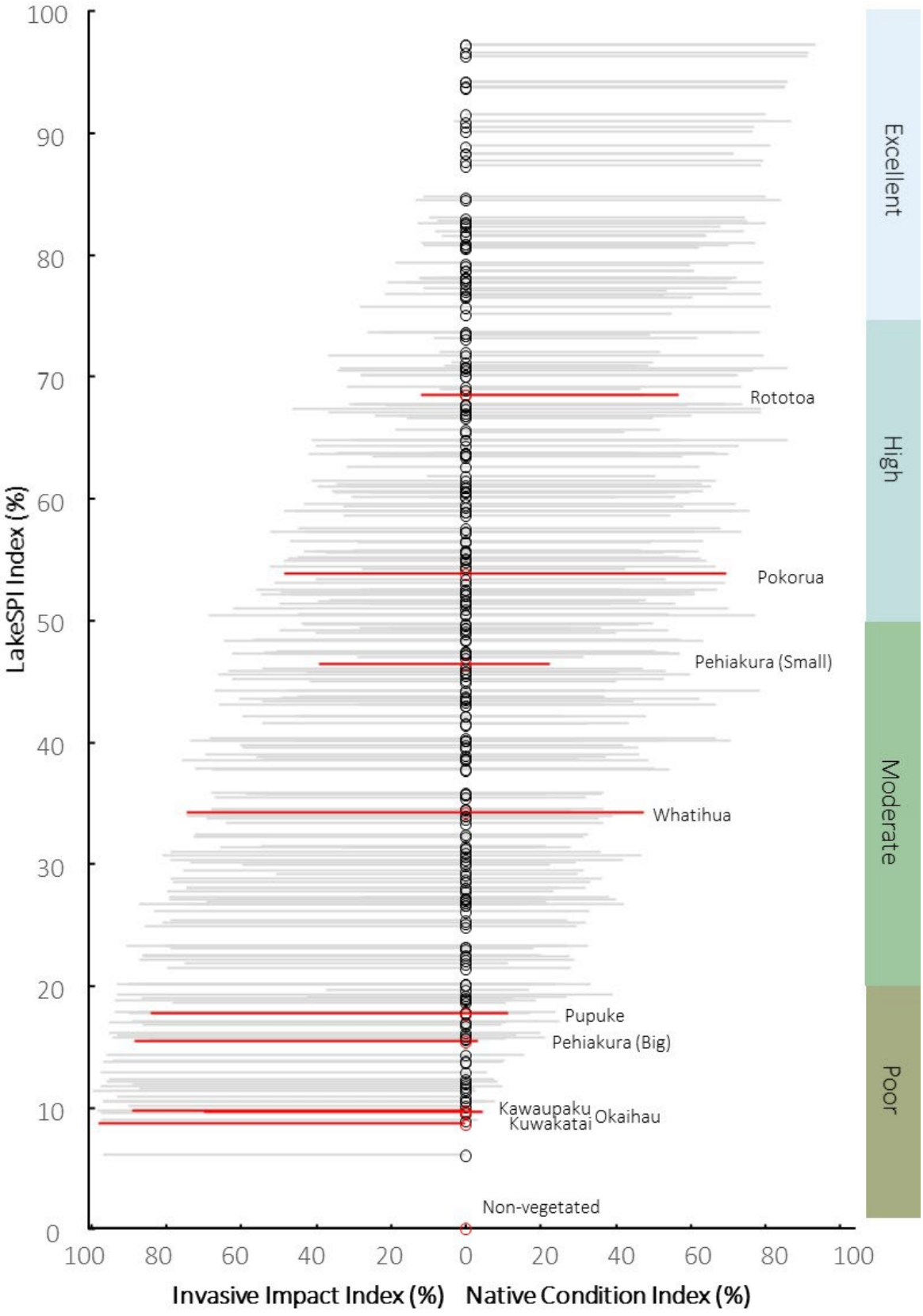


Figure 32 – The most recent LakeSPI scores for the Auckland region (red lines) are plotted with scores for a total of 333 New Zealand lakes. LakeSPI Index is plotted on the y-axis (points), Native Condition Index as lines to the right and Invasive Impact Index lines to the left. Five categories of LakeSPI condition are indicated. Lake names are listed with the exception of the 6 non-vegetated Auckland lakes.

4.1.1 High condition lakes

Two of the 15 lakes (13%) generated a high LakeSPI index (Table 3, Figure 32). These were Lake Rototoa (South Kaipara) and Lake Pokorua. The high LakeSPI indices reflected either substantial native vegetation character (Native Condition Index ≥50%), and/or the general absence of major impacts from invasive submerged weeds (Invasive Impact Index <50%).

4.1.2 Moderate condition lakes

Two of the 15 lakes (13%) were in moderate ecological condition (LakeSPI Index 34% and 46%), reflecting differing degrees of impact from invasive weeds (Table 3, Figure 32). Low impacts from invasive weeds (Invasive Impact Index 39%), but also restricted development by native vegetation (Native Condition Index 23%), were responsible for the scores at Lake Pehiakura Small (LakeSPI Index 46%). Another Awhitu Lake, Whatihua (LakeSPI Index 34%), had a strong invasive weed influence (Invasive Impact Index 78%), but also retained elements of native vegetation (Native Condition Index 48%).

4.1.3 Poor condition lakes

Five of the 15 lakes (33%) were grouped as being in poor ecological condition (LakeSPI ≤20%, Table 3, Figure 32), being strongly impacted by invasive weeds with an Invasive Impact Index ≥70%. Hornwort (*Ceratophyllum demersum*) or egeria (*Egeria densa*) are amongst the three highest ranked submerged plant species in New Zealand for 'weediness' (Champion and Clayton 2000) and are capable of completely replacing native elements in the vegetation, with these five lakes having a Native Condition Index ≤11%.

Additional signals of impacts from water quality are also common within this group either from documented retractions in depth extent and/or loss of sensitive native species such as charophytes. In the case of Lakes Okaihau, Kawaupaku and Kuwakatai impacts by coarse fish are also possible, based on previous fish records (New Zealand Freshwater Fish Database) and/or observations including vegetation disturbance and browsing.

4.1.4 Non-vegetated lakes

Six of the 15 lakes (40%) were categorised as being non-vegetated. LakeSPI cannot accurately represent lake ecological condition in Lake Kereta and Wainamu, where the management initiative of stocking grass carp to control weeds is responsible for vegetation absence. This is because the intervention results in a temporary modification of vegetation depth extent and diversity by grass carp, and several of the key assumptions behind the LakeSPI method (see Study methods) are not met.

In the remaining four lakes , the absence of submerged vegetation at >10% cover means they scored a LakeSPI and Native Condition Index of 0% (Table 3). These highly impacted lakes included two lakes that have previously recorded substantial submerged vegetation (Lakes Tomarata and Te Kanae) and two lakes that have been non-vegetated for >30 years (Spectacle and Slipper). Absence of significant vegetation generally indicates a highly impacted lake condition (de Winton et al. 2012) where, in most cases, water quality issues have created unfavourable conditions for submerged plant growth. However, other impacting factors can also contribute to a non-vegetated condition. Additional stressors in these lakes are likely to be grazing or disturbance by coarse fish. For instance, ongoing vegetation instability at Lake Tomarata is suspected be driven by fluctuating activity levels of exotic fish interacting with water quality conditions.

4.2 National comparison

Comparing the categories of lake ecological condition identified for the 15 Auckland region lakes to current LakeSPI Indices for 333 lakes nationally (Figure 20) shows:

- None of the 15 lakes fell into the 'excellent' category according to LakeSPI.
- A lower proportion of the 15 Auckland lakes were in the 'high' and 'moderate' category (13% in each category) compared to lakes nationally (52%).
- There is a much higher proportion (33%) of the 15 lakes in the 'poor' category than is the case nationally (13%).
- Auckland region had a much higher proportion of lakes (40%) which do not possess significant submerged vegetation and are categorised as 'non-vegetated' than is the case nationally (21%). We note two of the lakes have been stocked with grass carp to manage previously excessive submerged weed issues. Although they are included in this comparison, a LakeSPI assessment does not accurately indicate lake ecological condition in these biologically manipulated lakes.

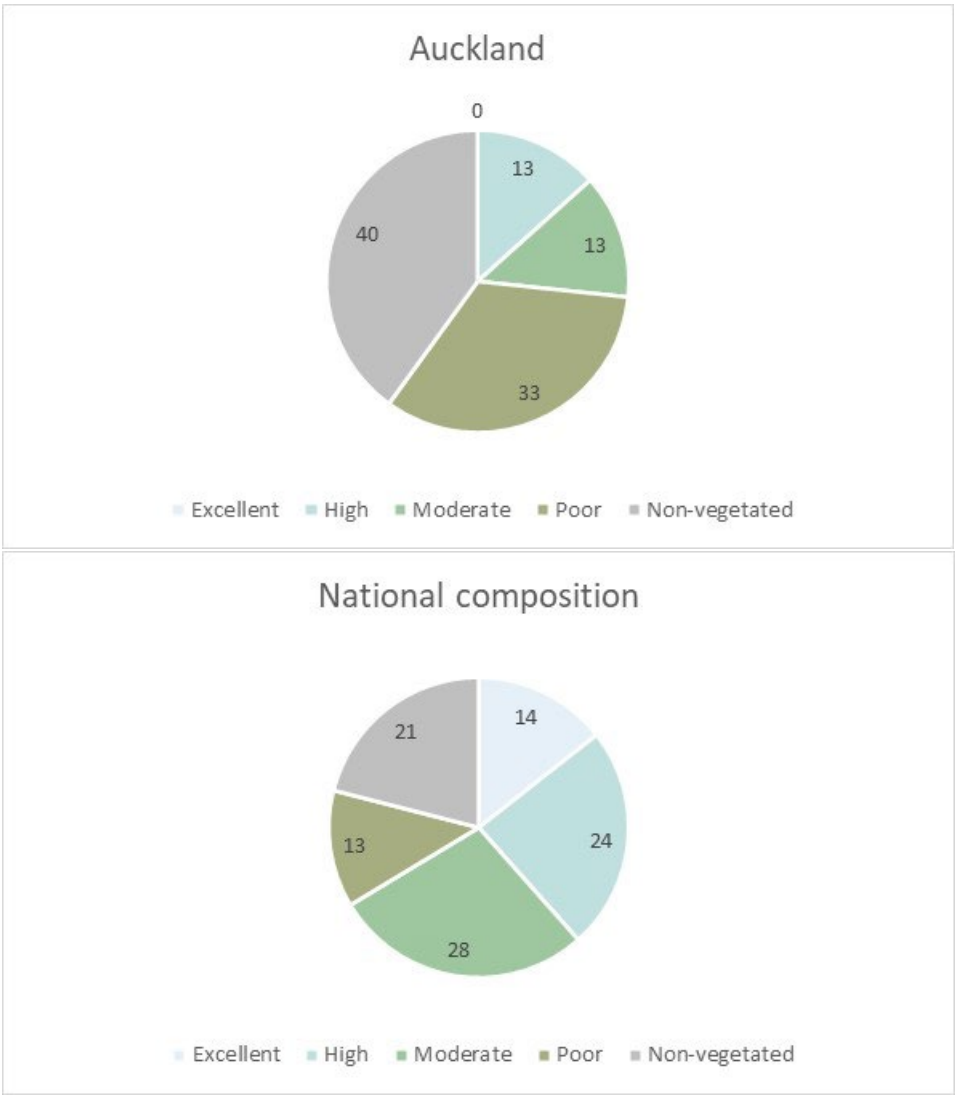


Figure 33 – Proportion of lakes that fall into each of five categories of LakeSPI Index for the Auckland region (15 surveyed lakes) and nationally (333 lakes), with percentage of lakes assessed shown for each category.

4.3 Stability in lake condition

Changes in LakeSPI indices between the last two assessments for each lake have been used to provide an indication of the current stability in lake condition and the direction of any change. Statistical analysis was also undertaken where possible (Table 4).

Of the 13 lakes that were suitable for LakeSPI assessment, seven appeared to be in a stable condition, with changes in LakeSPI score of ≤5% (Table 4). This group also includes Lake Pupuke, which has previously showed a declining condition (de Winton and Burton 2017) and the long-time non-vegetated Lakes Slipper and Spectacle. Lake Pehiakura Big did show a statistically significant improvement despite the small shifts in LakeSPI scores, but this improvement was countered by signs of vegetation stress under current algal bloom conditions. We conclude that these small shifts were not ecologically significant.

Table 4 – Lakes ranked in order of change in LakeSPI Index during the last two assessments, where comparisons are available.

	Statistical change between last two surveys			Category of change (%)	Change (%)	Stability
Lake	**LakeSPI Index**	**Native Condition Index**	**Invasive Condition Index**			
Tomarata	None	None	None	>15	-41	Declining
Pehiakura Small	None	None	None	>15	+26	Improving
Pokorua	+ve	None	-ve (improvement)	>10-15	+15	Improving
Okaihau	None	None	None	>5-10	-10	Declining
Te Kanae	-ve	None	-ve	>5-10	-10	Declining
Whatihua	None	None	None	>5-10	-7	Declining
Pehiakura Big	+ve	None	-ve (improvement)	≤5	+4	Stable
Kawaupaku	None	None	None	≤5	+2	Stable
Kuwakatai	None	None	None	≤5	+1	Stable
Rototoa	None	None	None	≤5	+1	Stable
Pupuke	None	None	None	0	0	Stable
Slipper	*	*	*	0	0	Stable
Spectacle	*	*	*	0	0	Stable
Kereta	-	-	-	-	-	Grass carp
Wainamu	-	-	-	-	-	Grass carp

* can't compute differences due to identical values

Lake Tomarata showed a large reduction (-41%) in lake ecological condition (Table 4) following a recent reversal of vegetation regeneration seen in 2020. Lake Tomarata was previously identified as having a declining ecological condition according to LakeSPI results over 2012 to 2017 (de Winton and Burton 2017). Three intervening assessments over 2019 to 2022 show this lake has lost its submerged vegetation for the second time, probably due to interactions between poor water clarity conditions for plant growth and on-going disturbance by populations of coarse fish.

Another three lakes with LakeSPI Index reductions of >5-10% showed a declining lake condition between the last two assessments (Table 4), although only one lake indicated statistically significant shifts. Lake Okaihau had previously been assessed as stable, Lake Te Kanae was surveyed only once previously and has since become 'non-vegetated' and Lake Whatihua was once again assessed as being in a declining ecological state, following this result in the previous assessment (de Winton and Burton 2017).

Two lake showed signs of improvement (Table 4). Lake Pokorua has shown significant improvement in the Invasive Impact Index over the last two assessments, and a significant increase in the LakeSPI Index in 2021 (Table 4). Earlier historical data suggests cycles of change and an unstable dominance by egeria (*Egeria densa*). Although Lake Pehiakura Small improved according to a large reduction in the Invasive Impact Index, the lake showed an overall reduction in vegetation abundance that leaves the lake just above the threshold for 'non-vegetated' lakes. For this reason, the 'improvement' may not be stable.

4.4 NPS-FM scoring

The attribute bands for 15 Auckland lakes are provided in Table 5. Thirteen per cent of the Auckland lakes (Lakes Wainamu and Kereta) are excluded from placement into attribute bands because LakeSPI is not an appropriate method for grass carp-stocked lakes.

According to the attribute entitled submerged plants – native (Native Condition Index), 15% of 13 assessed Auckland lakes (Lake Rototoa and Lake Pokorua) are placed into the B band, and 15% (Lake Pehiakura Small and Lake Whatihua) into the C band. Nine lakes (69%) fall below the national bottom line into the D band including Lakes Pupuke, Pehiakura Big, Kawaupaku, Okaihau, Kuwakatai, Te Kanae, Slipper, Spectacle and Tomarata.

The attribute submerged plants – invasive species (Invasive Condition Index) is not assigned for non-vegetated lakes, as these by definition cannot be invaded by weeds (Table 5). This attribute placed 11% of assessed Auckland lakes (Lake Rototoa) into the B band, 78% of lakes are placed into the C band (Lakes Pokorua, Pehiakura Small, Whatihua, Pupuke, Pehiakura Big, Kawaupaku and Okaihau). Only 11% of Auckland lakes (Lake Kuwakatai) fell below the national bottom line into the D band according to this attribute.

Table 5 – Attribute bands for the Native condition Index and Invasive Impact Index of 15 Auckland Lakes. – denotes lakes not assigned to bands.

Lake	Native Condition Index (%)	Invasive Impact Index (%)
Rototoa	B	B
Pokorua	B	C
Pehiakura Small	C	C
Whatihua	C	C
Pupuke	D	C
Pehiakura Big	D	C
Kawaupaku	D	C
Okaihau	D	C
Kuwakatai	D	D
Tomarata	D	-
Te Kanae	D	-
Slipper	D	-
Spectacle	D	-
Wainamu	-	-
Kereta	-	-

The current (2021/2022) proportion of lakes into attribute bands under the NPS-FM (2022) is shown for lakes nationally (Figure 34A), together with the proportion for lakes in the Auckland region Figure 34B). Band A lakes are not represented in Auckland region for either attribute, but nationally comprise 10% of lakes for National Condition Index and 14% for Invasive Impact Index (Figure 34A). Band B lakes for National Condition Index nationally comprise 29% of lakes, compared to 15% for Auckland lakes and C band comprise 28% nationally and 15% for Auckland lakes. Under the National Condition Index attribute, D band lakes for Auckland region comprise 69% compared to 33% of lakes nationally (Figure 34).

Under the Invasive Impact Index attribute, 14% of lakes nationally were graded as B band compared to 11% for Auckland Region, and 63% were graded as C band nationally compared to 78% of Auckland Lakes. The proportion of Auckland region lakes to fall below the national bottom line into the D band was similar for Auckland lakes, at 11%, as it was for lakes nationally at 10% (Figure 34).

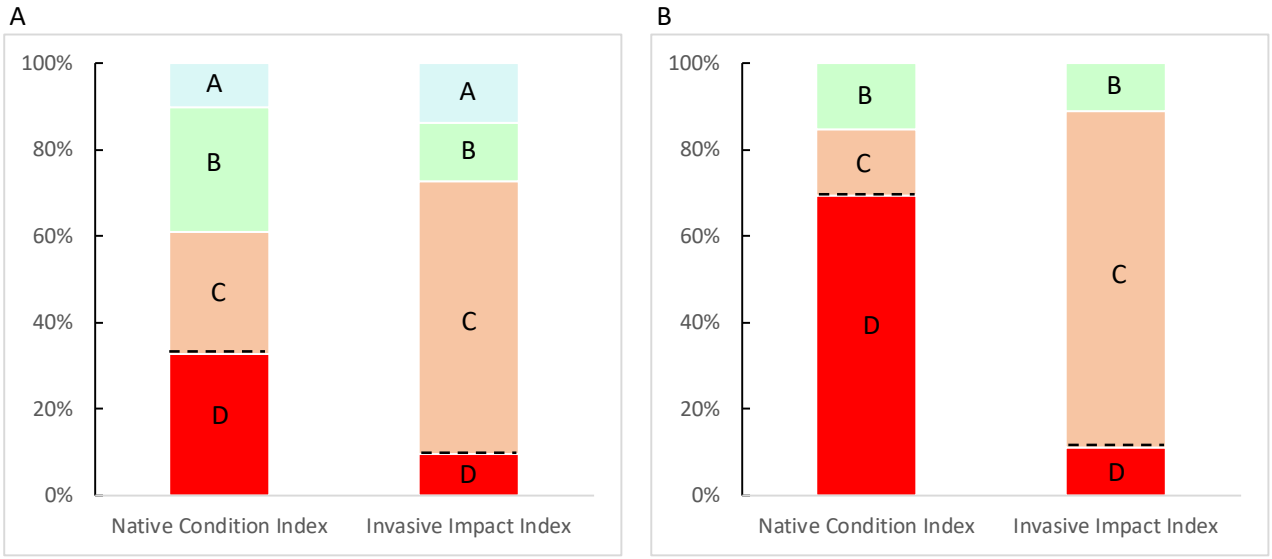


Figure 34 – Proportion of lakes in each attribute band for Native Condition Index and Invasive Impact Index, A) nationally and B) for Auckland Region. The black dotted line indicates the national bottom line. Number of assessed lakes for Native Condition Index is 333 nationally and 13 for Auckland region (grass carp stocked lakes excluded). Number of assessed lakes for Invasive Impact Index is 263 nationally and 9 for Auckland region (non-vegetated lakes excluded).

5. Conclusions and recommendations

Two out of the 15 surveyed Auckland lakes are not suitable for LakeSPI assessment, as component vegetation is artificially constrained by grass carp that were stocked to manage excessive aquatic weeds. None of the 13 remaining lakes were in an 'excellent' ecological condition according to the LakeSPI Index. Fifteen per cent (two lakes) were assessed as having a 'high' ecological condition and 15% as having a 'moderate' ecological condition. Thirty-nine per cent of lakes were in a 'poor' ecological condition. A further 31% of lakes did not have ecological significant development of submerged vegetation and were assesed as 'non-vegetated'.

According to the National Objectives Framework in the NPS-FM, 69% of assessed lakes in the Auckland region fell below the national bottom line. All 69% (nine lakes) graded in the D band for the Native Condition Index, with one of these lakes also graded in the D band for Invasive Impact Index, comprising 11% of the nine assessed lakes.

Several lakes in Auckland region are considered at high risk of further degradation. Loss of submerged vegetation and a switch to an algal dominated system is considered to be a worse ecological state than a highly weed invaded condition. From the latest 2021/2022 LakeSPI surveys, two lakes (Tomarata and Te Kanae) have been confirmed as having undergone a submerged vegetation decline event. Earlier vegetation decline events have been documented for two lakes (Wainamu and Kuwakatai), and Lakes Slipper and Spectacle have apparently been non-vegetated for over 34 years.

Risk of vegetation decline is considered highest for heavily invaded water bodies where weed beds occupy much of the water column, especially in the case of lakes invaded by egeria (Champion 2002) with 26.4% of the New Zealand lakes invaded by egeria subsequently undergoing a de-vegetation event (de Winton et al. 2009). Ultimately water quality degradation, possibly compounded by exotic fish disturbance, is the major driver of submerged vegetation loss. Signals for worsening water quality with climate change may increase the risk of submerged vegetation loss in the future.

Further aquatic weed and exotic fish invasion represent another risk to higher scoring lakes. Incursions of hornwort (*Ceratophyllum demersum*) to Lake Pupuke, Lake Pokorua, Lake Whatihua, the Pehiakura Lakes, Lake Kawaupaku or Lake Tomarata would be seen as the greatest risk. A range of exotic fish are already known from some of these waterbodies, but combinations of multiple herbivorous and benthivorous fish species in particular are likely to place stress on submerged vegetation development and persistence.

The NPS-FM (2022) states that monitoring of regionally selected lakes must be conducted once every three years for both LakeSPI attributes. For Auckland Region, lakes stocked with grass carp should be excluded from LakeSPI monitoring. However, the vegetation status of these lakes should be reviewed at five-yearly intervals, approximately (or after capture efforts) to determine if fish browsing pressure has reduced significantly to allow plant recovery. The remaining lakes should be resurveyed every three years, although there is scope to increase this to annual surveys if an intervention is undertaken or if a change in lake condition is suspected.

6. Acknowledgements

The authors would like to thank Daniel Clements (NIWA) and Dirk Immenga for field assistance. Jane Groom (Auckland Council) kindly provided access information and landowner contact details. We thank all landowners for access permission and route advice.

7. References

Burns, N.M.; Bowman, E.; Bryers, G. (2000). Protocol for Monitoring the Trophic Levels of New Zealand Lakes and Reservoirs. New Zealand Ministry for the Environment, Wellington NZ. 138 p.

Cadwallader, P.L. (1978). Acclimatisation of rudd *Scardinius erythrophthalmus* (Pisces: Cyprinidae), in the North Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research* 12: 81-82.

Champion P.D. (2002) *Egeria densa* – an alien invasive plant responsible for the loss of submersed vegetation from New Zealand shallow lakes. In: Spafford Jacob H, Dodd J, Moore JH ed. Perth, 13th Australian Weeds Conference papers and proceedings. Pp. 126-129.

Champion, P.D.; Clayton, J.S. (2000). Border control for potential aquatic weeds. Stage 1 – Weed risk model. Science for Conservation 141. Wellington, Department of Conservation.

Champion, P.D.; de Winton, M.D. (2005). Recommendations for management of Auckland Region's freshwater pests. NIWA Client Report HAM2005-137, prepared for Auckland Regional Council, 60 p.

Chapman V.J. (1970). A history of the lake-weed infestation of the Rotorua lakes and the lakes of the Waikato hydro-electric system. New Zealand Department of Scientific and Industrial Research Information Series, 78: 1-52.

Clayton, J.; Edwards, T. (2006). Aquatic plants as environmental indicators of ecological condition in New Zealand lakes. *Hydrobiologia* 570: 147-151.

Coffey, B.T.; Clayton, J.S. (1987). Submerged macrophytes of Lake Pupuke, Takapuna, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 21: 193-190.

Crivelli, A.J. (1983). The destruction of aquatic vegetation by carp, a comparison between Southern France and the United States. *Hydrobiologia* 106: 37-41.

Cunningham, B.T.; Moar, N.T.; Torrie, A.W.; Parr, P.J. (1953). A survey of the western coastal dune lakes of the North Island, New Zealand. *Australian Journal of Marine and Freshwater Research* 4: 34-386.

de Winton M. (2010) Aquatic weed distribution in west Auckland lakes – February 2010, NIWA Client Report: HAM2010-020, Prepared for Auckland Regional Council, 24 pp.

de Winton M.D., Clayton, J.S., Edwards, T. (2012). Incorporating invasive weeds into a plant indicator method (LakeSPI) to assess lake ecological condition. *Hydrobiologia*. 691: 47-58.

de Winton, M. and Burton, T. (2017). LakeSPI assessment of 33 Auckland Lakes: 2017 update. Prepared by NIWA for Auckland Council. Auckland Council technical report, TR2017/028. 110 pp

de Winton, M.D.; Champion, P.D.; Clayton, J.S.; Wells, R.D.S. (2009). Spread and status of seven submerged pest plants in New Zealand lakes. *New Zealand Journal of Marine and Freshwater* 43: 547-561.

de Winton, M.D.; Taumoepeau, A.T.; Clayton, J.S. (2002). Fish effects on charophyte establishment in a shallow, eutrophic New Zealand lake. *NZ Journal of Marine and Freshwater Research* 36: 815-823.

Dugdale; T. M. Hicks; B.J.; de Winton; M.D. Taumoepeau; A.T. (2006). Fish exclosures versus intensive fishing to restore charophytes in a shallow New Zealand lake. *Aquatic conservation: Marine and freshwater ecosystems,* 16:193-202.

Gibbs, M.; Boothroyd, I.; Champion, P.; Green, J.; Duggan, I. (1999). ARC lakes monitoring programme review. NIWA Client Report ARC00256.

Hamill, K.D., Lockie, S.E. (2015) State of the environment monitoring. Auckland lake water quality: state and trends. Auckland Council technical report, TR2015/007.

Lake, M.D., Hicks, B.J., Wells, R.D.S., Dugdale, T.M. (2002) Consumption of submerged aquatic macrophytes by rudd (*Scardinius erythrophthalmus* L.) in New Zealand. *Hydrobiologia* 470, 13-22.

Rowe, D.K. (2007). Exotic fish introductions and the decline of water clarity in small North Island, New Zealand lakes: a multi-species problem. *Hydrobiologia* 583: 345-358.

Schallenberg M., Sorrell B. (2009) Regime shifts between clear and turbid water in New Zealand lakes: Environmental correlates and implications for management and restoration, *New Zealand Journal of Marine and Freshwater Research*, 43:3, 701-712.

Wells R. (2016). The impacts of recreational activities on Lake Tomarata's ecology and water quality. Auckland Council technical report, TR2016/033. NIWA Project: HSJ16221, 22pp.

Wood, R.D.; Mason, R. (1977). Characeae of New Zealand. *New Zealand Journal of Botany* 15: 87-180.

Appendix A

History of lakes of the Auckland region

The Auckland region has approximately 72 water bodies of 1 ha in size or greater (Freshwater Ecosystems of New Zealand geo-database[3]), ranging in size from small ponds to several large flooded valleys which serve as reservoirs for reticulated water supply. Lake types in the region can be categorised depending on their location and how they were formed. These types include sand dune lakes along the western and eastern coasts, water bodies of volcanic origin in the city of Auckland and constructed reservoirs for water storage and abstraction, mainly in the Waitakere and Hunua Ranges.

Prior to people arriving in New Zealand, naturally formed lakes would have been in their natural 'pristine' state. Periodic disruption to lake condition would have occurred with natural disturbances, such as volcanic activity, flood events or from dynamic aeolian dune processes. Changes in lake condition also took place as the lakes aged, with key influences being changing climatic conditions, changes in catchment vegetation and progressive nutrient enrichment associated with increased productivity. Native submerged plant communities were likely present in all natural Auckland lake types as evidenced by early botanists. For example, Cheeseman collected six species of native charophyte from Lake Pupuke in 1884 (Wood and Mason 1977) and Cunningham et al. (1953) reported extensive native plant communities in five coastal dune lakes within the region.

The early history of land settlement, scale of land use change and proximity to a large population centre meant that lakes in the Auckland region have been especially vulnerable to change. Three major factors cause the accelerated decline in ecological condition of lakes: (1) declining water quality; (2) invasive fish species; and (3) invasive plant species.

Declining water quality typically results from the conversion of natural forested lake catchments to agriculture, exacerbated by drainage of wetlands and removal of lake-margin vegetation, fertiliser application to pasture, and further impacts from farming activities which, collectively, lead to accelerated nutrient enrichment and siltation. The result is increased productivity at an unnatural rate and dominance of phytoplankton over submerged plants so that lakes may ultimately become de-vegetated and turbid.

In recent years there has been widespread liberation of invasive exotic fish such as rudd (*Scardinius erythrophthalmus*) and koi carp (*Cyprinus carpio*), which have contributed significantly to the deterioration in water quality (Rowe 2007) and the decline of submerged vegetation. Juvenile stages of many invasive exotic fish, and some adult stages, feed on zooplankton and so may release planktonic algae from the grazing control exerted by zooplankton (Rowe 2007). Exotic fish also contribute to increased sediment re-suspension in lakes and can reduce plant cover (Rowe 2007). Herbivorous rudd directly graze on submerged vegetation (de Winton et al. 2003), whilst exotic fish are also implicated in preventing the re-establishment of vegetation from propagules, which contributes to the present poor status of many turbid non-vegetated lakes.

Thirdly, there has been extensive invasion of most lakes by submerged weed species that have largely displaced native submerged vegetation. The earliest recorded weed introduction was *Elodea canadensis*, which arrived in New Zealand in the late 1800s and was subsequently spread around much of the country (Chapman 1970). Cheeseman (1886) recorded the early establishment of *Vallisneria australis* (as *V. spiralis*) in Lake Pupuke. Successively more competitive submerged weeds established in New Zealand

[3] http://www.doc.govt.nz/our-work/freshwater-ecosystems-of-new-zealand

lakes, firstly lagarosiphon *(Lagarosiphon major)*, then egeria (*Egeria densa*) and hornwort (*Ceratophyllum demersum)*. Their combined effect has led to the virtual loss of submerged native plants from many lakes. Subsequent rapid and wide scale declines in the abundance of weed-dominated vegetation, particularly egeria (Champion 2002), has occurred in fifteen or more New Zealand lakes including Lake Wainamu in the Auckland region (de Winton et al. 2007). In non-vegetated lakes, high biomass algal growth or re-suspension of bottom sediments often reduces water clarity to the point where aquatic plants have not re-established.

Lake vegetation changes

In a pristine state, lakes in the Auckland region would have once contained a diverse range of native plant species to a depth determined by water clarity or the maximum depth of the lake (Figure 35). For very shallow lakes (i.e., <10 m depth) it is likely that plant growth would have occurred across the entire lake bottom at some stage during their development and maturation. Today, there are relatively few lakes in New Zealand that remain in an all-native vegetated state.

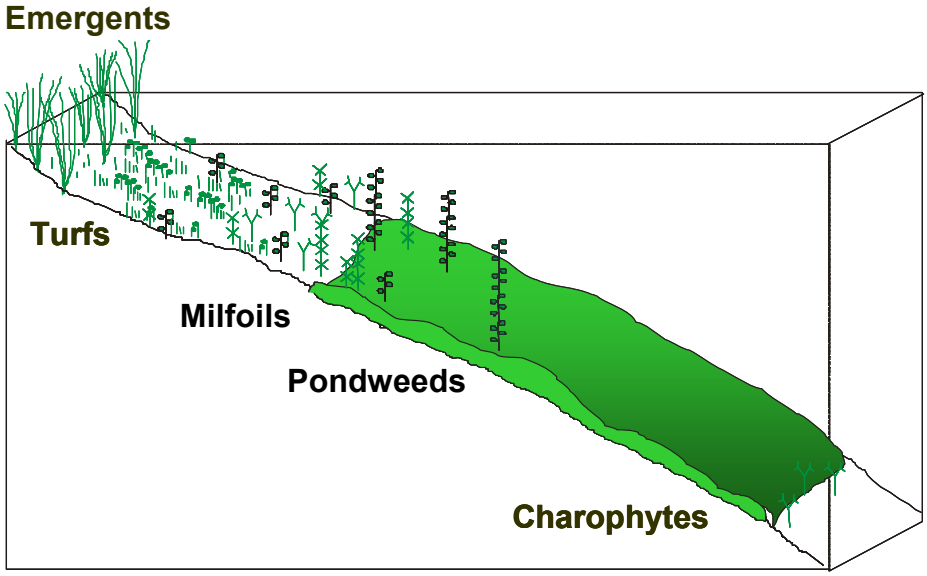


Figure 35 – Depth profile illustrating the main components of native lake vegetation.

With the introduction of invasive submerged plant species during the mid-1900s, native plants in most lakes were displaced by invasive weed species, often forming tall monospecific weed beds (Figure 36), which were then especially vulnerable to subsequent decline and dominance by phytoplankton or turbid water conditions (Figure 37). Although invasive weeds are not favourable in terms of overall lake condition, the presence of any submerged plants in a lake is preferable to none, because they mitigate many of the symptoms of eutrophication (e.g., lock-up nutrients, maintain water clarity, compete with phytoplankton).

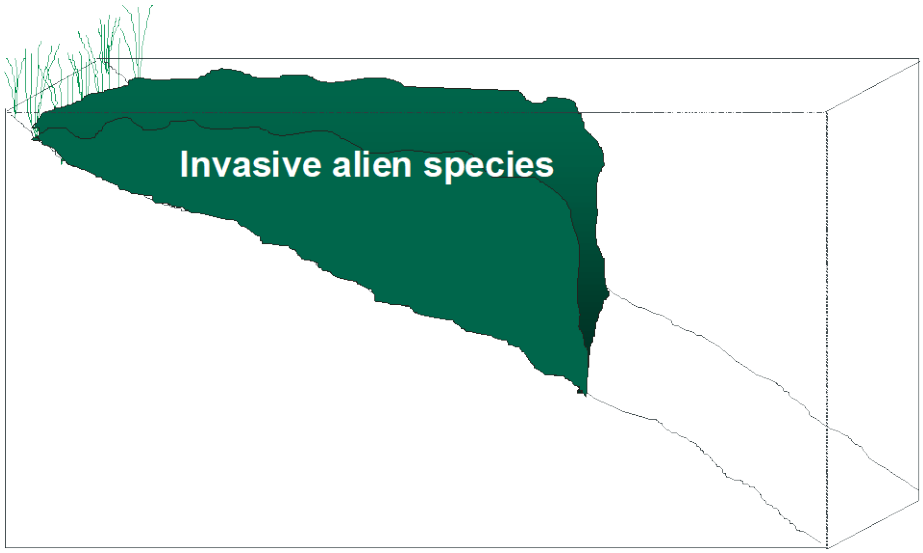


Figure 36 – Depth profile illustrating the potential impact of invasive species.

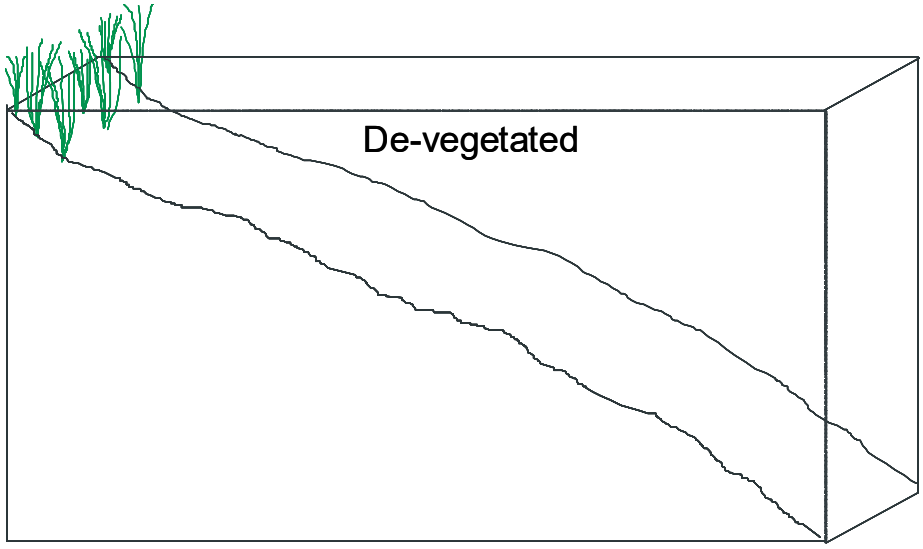


Figure 37 – Depth profile illustrating a non-vegetated lake.

Plants as indicators of lake condition

Submerged plants have a number of advantages that favour their use as indicators of lake condition. For example, they are predominantly rooted or anchored to the bed of lakes. They are also macroscopic and perennial in nature, and together these features make them easy to observe, sample and identify. This contrasts with many other biota that can be highly mobile (e.g., fish) or difficult to sample, measure or identify (e.g., plankton).

Submerged plants also effectively integrate the range of environmental conditions supporting plant growth over an extended period of time prior to survey. This contrasts with other physico-chemical methods (e.g., water chemistry and Secchi disc), which may change markedly over short time periods and require frequent measurements throughout the year.

In lakes where the littoral zone (lake margin to maximum plant depth) represents a large proportion of the lake area (e.g., small shallow dune or peat lakes), the open water (or lake centre) condition can have quite different water quality and ecological condition compared to the littoral zone. Given the importance of the

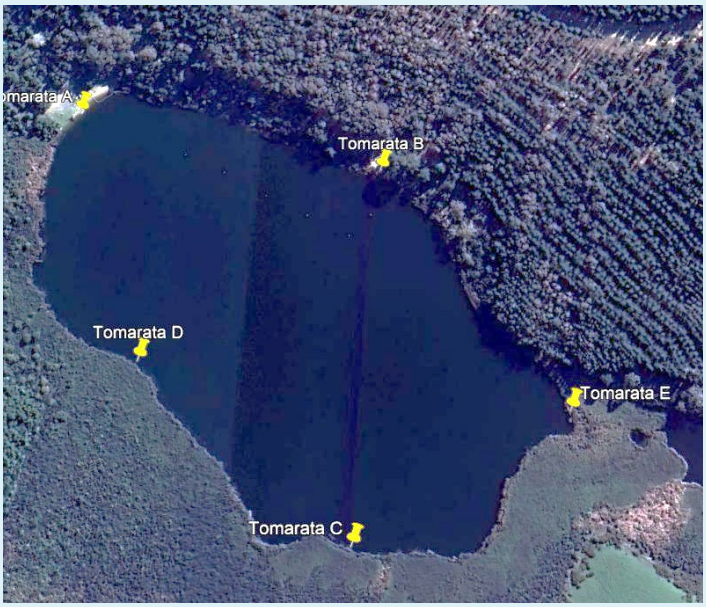
littoral zone to the overall ecological state and recreational value of many lakes it is important to monitor the ecological well-being and biological functioning of the littoral zone where submerged plants tend to dominate.

Increased sediment and nutrient loading from catchment activities, and displacement of native vegetation by invasive alien plant species, are major influences on lake ecology and condition. The submerged plant indicators used in LakeSPI provide an effective means of assessing these impacts.

Appendix B

Site maps and GIS references

Tomarata map



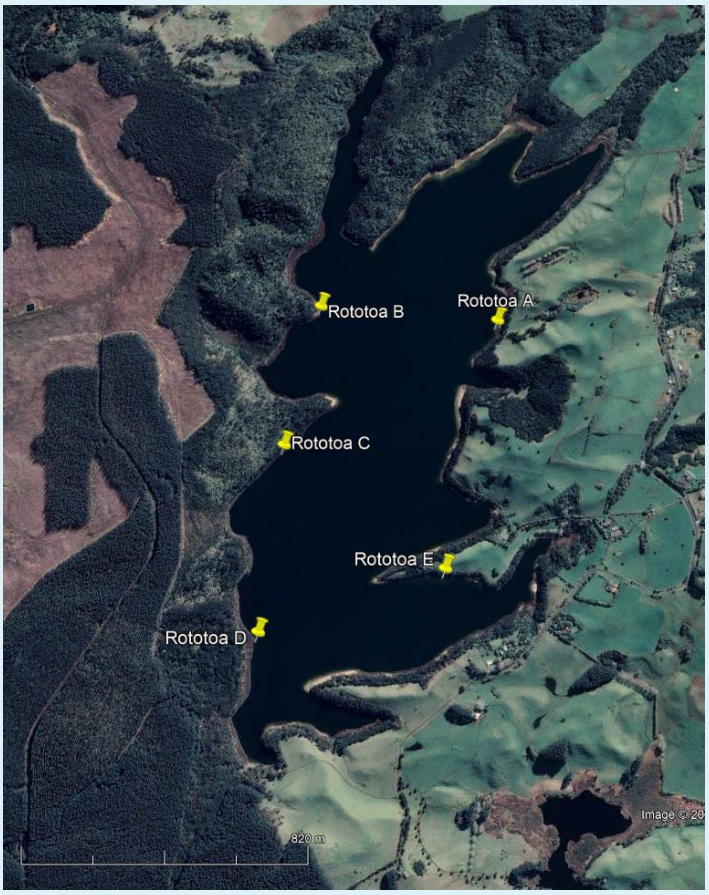
Lake and site	Northing	Easting
Tomarata A	36 11.508	174 38.856
Tomarata B	36 11.541	174 39.058
Tomarata C	36 11.737	174 39.055
Tomarata D	36 11.644	174 38.913
Tomarata E	36 11.670	174 39.186

Spectacle map

Lake and site	Northing	Easting
Spectacle A	36 10.812	174 37.999
Spectacle B	36 10.912	174 37.655
Spectacle C	36 11.216	174 38.200

Slipper map

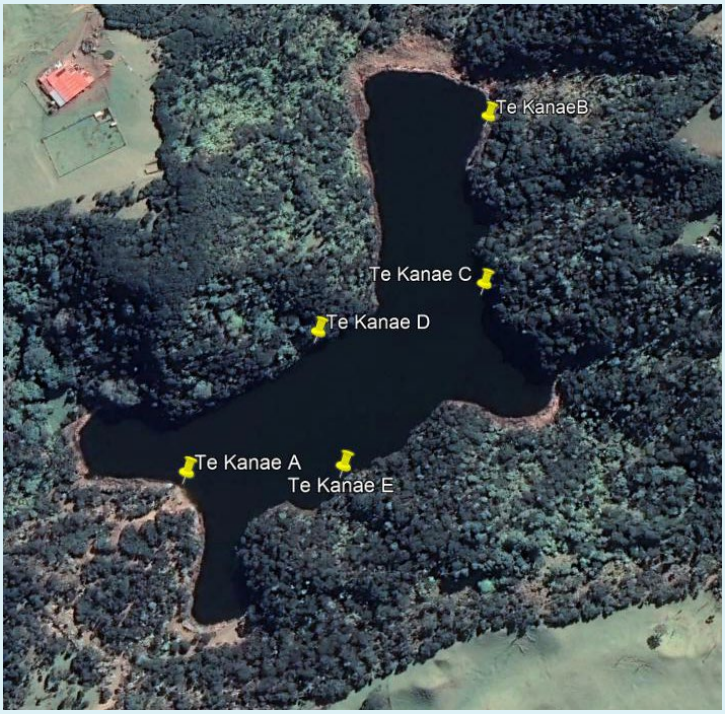

Lake and site	Northing	Easting
Slipper A	36 10.256	174 37.817
Slipper B	36 10.435	174 37.765
Slipper C	36 10.350	174 37.859

Rototoa map


Lake and site	Northing	Easting
Rototoa A	36 30.531	174 14.477
Rototoa B	36 30.507	174 14.104
Rototoa C	36 30.748	174 14.050
Rototoa D	36 31.055	174 14.028
Rototoa E	36 30.952	174 14.394

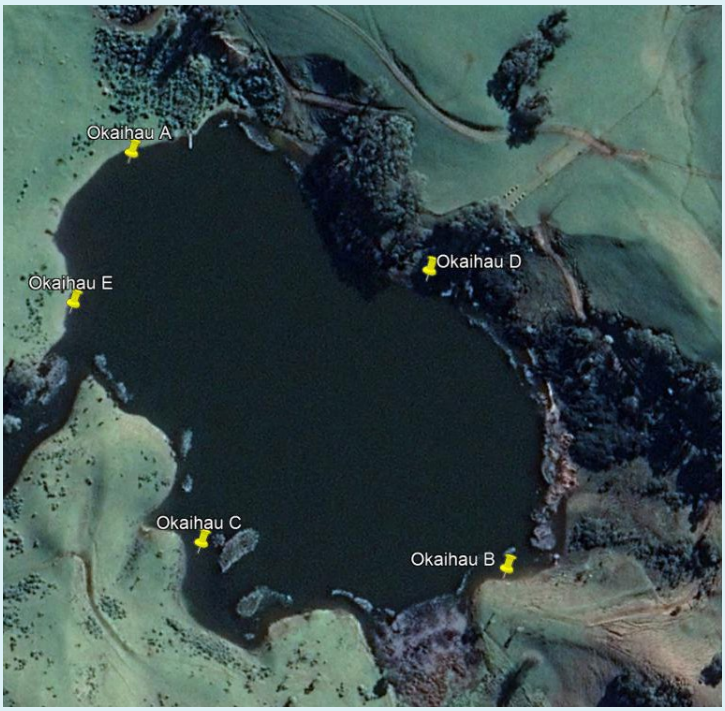
Kuwakatai map

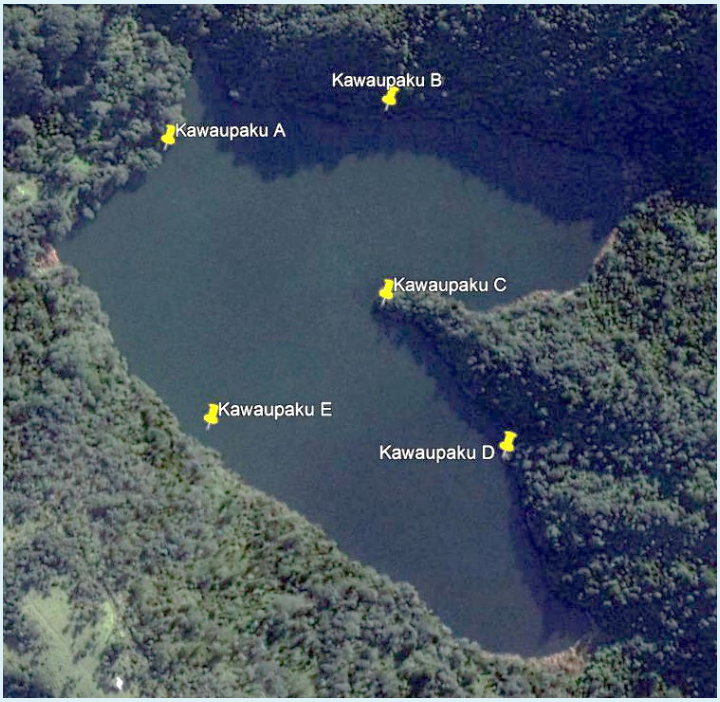

Lake and site	Northing	Easting
Kuwakatai A	36 31.904	174 14.021
Kuwakatai B	36 31.768	174 14.158
Kuwakatai C	36 31.646	174 14.656
Kuwakatai D	36 31.651	174 14.531
Kuwakatai E	36 31.683	174 14.136

Te Kanae map


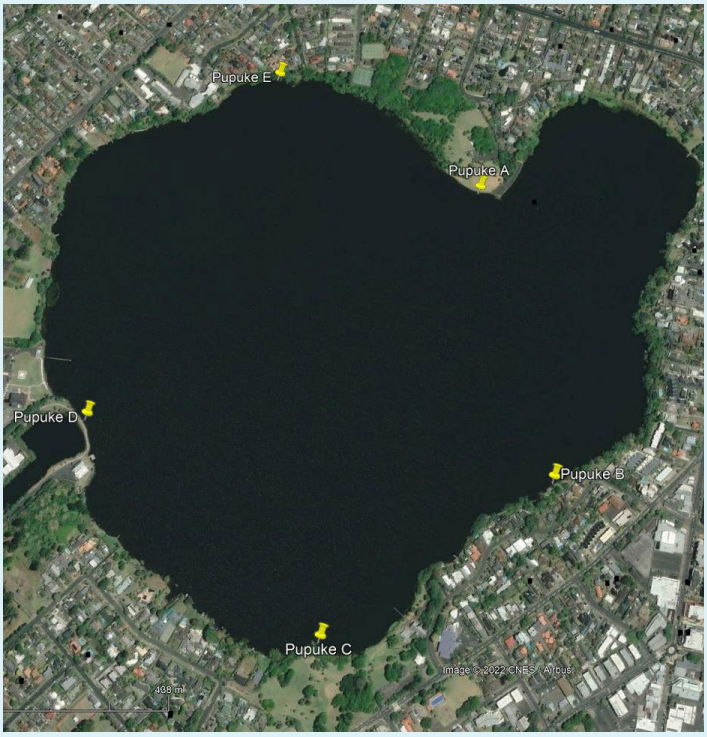
Lake and site	Northing	Easting
Te Kanae A	36 34.697	174 17.237
Te Kanae B	36 34.531	174 17.378
Te Kanae C	36 34.612	174 17.387
Te Kanae D	36 34.637	174 17.297
Te Kanae E	36 34.694	174 17.319

Kereta map	Lake and site	Northing	Easting
	Kereta A	36 35.670	174 16.908
	Kereta B	36 35.769	174 17.040
	Kereta C	36 35.875	174 17.223
	Kereta D	36 35.290	174 16.506
	Kereta E	36 35.545	174 16.923

Okaihau map	Lake and site	Northing	Easting
	Okaihau A	36 48.501	174 26.343
	Okaihau B	36 48.612	174 26.483
	Okaihau C	36 48.600	174 26.370
	Okaihau D	36 48.529	174 26.458
	Okaihau E	36 48.543	174 26.332

Kawaupaku map	Lake and site	Northing	Easting
	Kawaupaku A	36 53.620	174 27.444
	Kawaupaku B	36 53.603	174 27.558
	Kawaupaku C	36 53.683	174 27.563
	Kawaupaku D	36 53.740	174 27.630
	Kawaupaku E	36 53.736	174 27.474

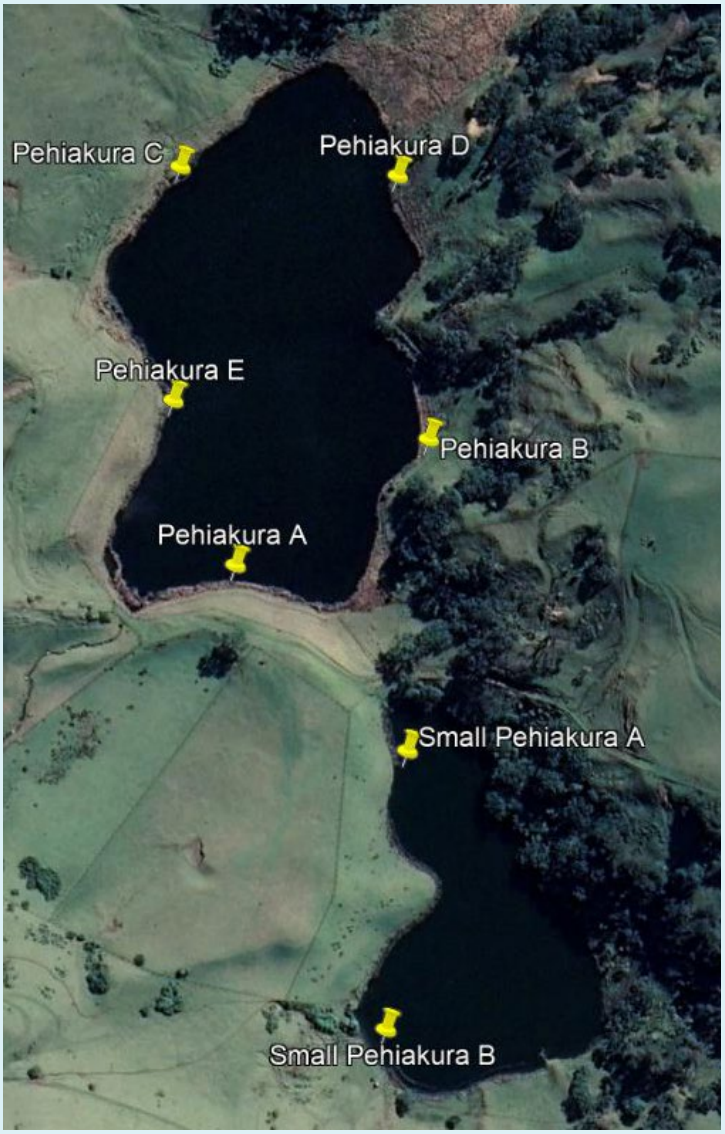
Wainamu map	Lake and site	Northing	Easting
	Wainamu A	36 53.208	174 27.981
	Wainamu B	36 53.375	174 28.179
	Wainamu C	36 53.473	174 28.438
	Wainamu D	36 53.475	174 28.257
	Wainamu E	36 53.398	174 28.024

Pupuke map	Lake and site	Northing	Easting
	Pupuke A	36 46.659	174 46.137
	Pupuke B	36 46.978	174 46.236
	Pupuke C	36 47.140	174 45.938
	Pupuke D	36 46.912	174 45.620
	Pupuke E	36 46.524	174 45.853

Pokorua map	Lake and site	Northing	Easting
	Pokorua A	37 11.654	174 37.978
	Pokorua B	37 11.612	174 38.180
	Pokorua C	37 11.462	174 38.105
	Pokorua D	37 11.449	174 37.931
	Pokorua E	37 11.599	174 37.758

Whatihua map


Lake and site	Northing	Easting
Whatihua A	37 16.562	174 40.162
Whatihua B	37 16.528	174 40.276
Whatihua C	37 16.502	174 40.194
Whatihua D	37 16.544	174 40.100
Whatihua E	37 16.476	174 40.275

Pehiakura map


Lake and site	Northing	Easting
Pehiakura Big A	37 11.016	174 36.865
Pehiakura Big B	37 10.974	174 36.946
Pehiakura Big C	37 10.883	174 36.842
Pehiakura Big D	37 10.886	174 36.933
Pehiakura Big E	37 10.961	174 36.839
Pehiakura Small A	37 11.078	174 36.937
Pehiakura Small B	37 11.171	174 36.928

Appendix C

Species lists for LakeSPI surveys since 2017

Table 6 – Aquatic plant species reported in the Te Arai lakes. = non indigenous*

Species	Lake Tomarata 2019	Lake Tomarata 2020	Lake Tomarata 2022	Lake Spectacle 2022	Lake Slipper 2022
Emergents					
Apodasmia similis		✓	✓		
Machaerina articulata	✓	✓	✓		✓
Eleocharis sphacelata	✓	✓	✓	✓	
Typha orientalis		✓	✓	✓	✓
Machaerina juncea			✓		
Eleocharis acuta					✓
Schoenoplectus tabernaemontani					✓
Invasive weeds					
**Utricularia gibba*		✓	✓		
Charophytes					
Chara australis	✓	✓	✓		
Nitella pseudoflabellata	✓	✓	✓		
Nitella sp. aff. *cristata*	✓				
Nitella leonhardii		✓			
Other					
**Alternanthera philoxeroides*					✓
Carex secta					✓
**Ludwigia palustris*					✓
Isolepis prolifer					✓

Table 7 – Aquatic plant species reported in the South Kaipara lakes. = non indigenous.*

Species	Rototoa 2019	Rototoa 2022	Kuwakatai 2022	Te Kanae 2022	Kereta 2022
Emergents					
Apodasmia similis	✓	✓			
Eleocharis sphacelata	✓	✓	✓	✓	
Machaerina arthrophylla	✓	✓			
Machaerina articulata	✓	✓	✓	✓	
Typha orientalis	✓				✓
Invasive weeds					
**Ceratophyllum demersum*	✓	✓	✓	✓	
**Utricularia gibba*	✓	✓			
Pondweeds					
Potamogeton cheesemanii	✓	✓			
Potamogeton ochreatus	✓	✓			
Milfoils					
Myriophyllum propinquum					✓
Charophytes					
Chara australis	✓	✓			
Chara fibrosa	✓	✓			
Chara globularis	✓	✓			
Nitella hyalina	✓	✓			
Nitella leonhardii	✓	✓			
Nitella pseudoflabellata		✓			
Other					
**Alternanthera philoxeroides*					✓
Isolepis prolifer					✓
**Ludwigia palustris*					✓
**Ludwigia peploides*					✓

*Table 8 – Aquatic plant species reported in the Muriwai lakes. * = non indigenous.*

Species	Okaihau 2022	Kawaupaku 2022	Wainamu 2022
Emergents			
Eleocharis sphacelata		✓	✓
Machaerina articulata		✓	✓
Typha orientalis		✓	✓
Turf plants			
Glossostigma elatinoides	✓		
Invasive weeds			
**Ceratophyllum demersum*	✓		
**Egeria densa*		✓	
**Utricularia gibba*			✓
Charophytes			
Nitella sp. aff. *cristata*	✓		✓
Chara australis			✓
Other			
**Ludwigia peploides*			✓
**Nymphaea* sp.	✓		

*Table 9 – Aquatic plant species reported in Lake Pupuke. * = non indigenous.*

Species	Pupuke 2022
Invasive weeds	
**Egeria densa*	✓
**Vallisneria australis*	✓
Charophytes	
Chara australis	✓
Milfoils	
Myriophyllum triphyllum	✓

Table 10 – Aquatic plant species reported in the Awhitu lakes. = non indigenous.*

Species	Pokorua 2021	Whatihua 2021	Small Pehiakura 2021	Big Pehiakura 2021
Emergents				
Bolboschoenus fluviatilis				✓
Eleocharis acuta		✓		
Eleocharis sphacelata		✓		
Machaerina articulata				✓
Schoenoplectus tabernaemontani		✓	✓	✓
Typha orientalis				✓
Turf Plants				
Glossostigma elatinoides		✓	✓	
Lilaeopsis ruthiana		✓		
Limosella lineata		✓		
Invasive weeds				
**Egeria densa*	✓	✓	✓	✓
**Elodea canadensis*	✓	✓		
**Utricularia gibba*		✓		
Pondweeds				
Potamogeton cheesemanii		✓		
Potamogeton ochreatus	✓	✓		
Milfoils				
Myriophyllum triphyllum	✓	✓	✓	
Charophytes				
Chara australis	✓	✓		✓
Chara fibrosa		✓		
Chara globularis		✓		
Nitella hyalina	✓	✓		✓
Nitella pseudoflabellata		✓		
Nitella sp. aff. *cristata*	✓			
Other				
Persicaria decipiens		✓		
Zannichellia palustris	✓			
**Azolla pinnata*		✓		

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